

Nuclear Thermal Propulsion Technology: Results of an Interagency Panel in FY 1991

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**NUCLEAR THERMAL PROPULSION TECHNOLOGY:
RESULTS OF AN INTERAGENCY PANEL IN FY 1991**

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FOREWORD

NASA, DoD, and the DOE have jointly initiated technology development for nuclear rocket propulsion systems for the U.S. Space Exploration Initiative (SEI) missions to the Moon and to Mars. In 1991, six interagency panels were established to address various issues associated with nuclear propulsion technology, and to assist in planning for the technology development project. Both nuclear thermal and nuclear electric propulsion systems are included in the project. This paper summarizes the planning activities and recommendations of the interagency nuclear thermal propulsion (NTP) technology team in FY 1991, and also summarizes the major recommendations of the other five panels. Separate detailed final reports will also be published by each of the panels.

The NTP panel was assembled following an NTP workshop held in July, 1990, in Cleveland, Ohio. The workshop provided an assessment of the state-of-the-art of nuclear thermal propulsion technology, and identified a number of issues that must be addressed to enable nuclear thermal propulsion systems to become a reality. A substantial technology data base was developed in the 1960s and early 1970s for solid core nuclear thermal reactors, in the ROVER/NERVA program, as well as the nuclear airplane program. At the same time, closed cycle gas core nuclear systems were also explored by the United Technologies Research Corporation and others for NASA and the Atomic Energy Commission.

Nuclear technologists today believe that this earlier technology can be improved by incorporating advanced fuels and materials, high performance turbopumps and nozzles, and by utilizing improved computational capability that was not possible 30 years ago. Improved instrumentation and control systems and nuclear fuels could also permit higher operating temperatures, with appropriate safety and reliability margins. Ultimately, the "first generation" solid core reactors may be upgraded to even higher temperature liquid or gaseous core concepts, to provide even better performance, when these technologies can be developed and validated. Thus, an evolutionary, step-wise technology development project is planned to have systems ready for initial unmanned flights by about 2008, will include robotic lunar missions to gain operational experience prior to manned flight, and will then proceed to a manned lunar mission that will simulate a full-up Mars mission. Mars robotic missions are planned to begin in late 2011, with the first manned Mars mission in about 2014. An approach that would permit earlier NTR flights was also presented at the NTP workshop, and is discussed briefly in this report.

The authors wish to acknowledge the guidance provided to the NTP technology team by the workshop steering committee: Dr. Gary Bennett of NASA Headquarters, Code RP; Mr. Earl Wahlquist of the DOE Office of Nuclear Energy, and Lt. Col. Roger Lenard of the Air

Force Phillips Laboratory. Mr. Tom Miller of NASA-Lewis was Executive Secretary of the Steering Committee, and astronaut Franklin Chang-Diaz also served as an "Ex-Officio" member of the steering committee. Many thanks also to the seventeen government members of the NTP panel and the twenty-eight industry, academic, and other observers, without whose expertise and participation this collaborative planning could not have been possible. The primary contributors to this final report are included as co-authors, and their efforts are most gratefully acknowledged.

This report represents a consensus opinion of the NTP Technology Panel members, and does not necessarily represent the official views of NASA, DoD, or DOE. No inferences should be drawn from this report regarding official funding commitments or policy decisions.

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EXECUTIVE SUMMARY

The NASA Lewis Research Center was selected to lead nuclear propulsion technology development for NASA. Also participating in the project are NASA Marshall Spaceflight Center and the Jet Propulsion Laboratory. The U.S. Department of Energy will develop nuclear technology and will conduct nuclear component, subsystem, and system testing at appropriate DOE test facilities. NASA program management is the responsibility of NASA/RP. The project includes both nuclear electric propulsion (NEP) and nuclear thermal propulsion (NTP) technology development.

This report summarizes the efforts of an interagency panel that evaluated NTP technology in 1991. Other panels were also at work in 1991 on other aspects of nuclear propulsion, and the six panels worked closely together. The charters for the other panels and some of their results are also discussed. Important collaborative efforts with other panels are highlighted.

The interagency (NASA/DOE/DOD) NTP Technology Panel worked in 1991 to evaluate nuclear thermal propulsion concepts on a consistent basis, and to continue technology development project planning for a joint project in nuclear propulsion for the Space Exploration Initiative (SEI). Five meetings of the panel were held in 1991 to continue the planning for technology development of nuclear thermal propulsion systems. The state-of-the-art of the NTP technologies was reviewed in some detail. The major technologies identified were: fuels, coatings, and other reactor technologies; materials; instrumentation, controls, health monitoring and management, and associated technologies; nozzles; and feed system technology, including turbopump assemblies.

CONSISTENT CONCEPT COMPARISON

The concepts presented at the 1990 NTP Workshop were reviewed in detail. Of the solid core concepts presented, it was the consensus that any of the three reactor types, thermal, heterogeneous, or fast reactors, could be developed through full system ground test completion (TRL-6) by 2006, provided adequate funding is provided. In addition, it is believed that several other concepts could also be developed to TRL-6 by 2006, provided (1) they overcome relevant "proof-of-concept" issues, and (2) adequate funding is provided; development of these concepts may be higher cost. These concepts are:

- the low pressure solid core concept,
- the closed cycle gas core "Nuclear Light Bulb" concept, and
- the closed cycle vapor core reactor concept.

Proof-of-concept testing and analysis of these concepts will be a high priority in the project as "Innovative Technology."

Nineteen concepts were reviewed and compared. Many advanced concepts, that may offer significant performance improvement, were believed to be unable to reach TRL-6 by 2006 because of the technical risks inherent in the concepts. These "innovative" concepts will also be studied in the technology development project, and the NTP panel recommended that about ten percent of the budget be used to evaluate these innovative concepts. An "Innovative Concepts" Subpanel identified and prioritized innovative concepts, and identified a number of proof-of-concept tests that should be conducted.

While further studies will be required to provide a consistent comparison of all of the NTP concepts, the current status of the comparison studies is presented. A detailed study methodology was defined and a parameter space identified by the panel. Attributes to be used to compare systems were selected:

- specific impulse,
- initial mass in low earth orbit,
- engine thrust,
- engine thrust/weight, and
- propellant exit temperature.

Safety, reliability and risk management were also identified as important attributes for all SEI missions. Scaling parameters were identified for the NERVA-derived reactor (NDR) concepts. Design trade studies were conducted using a modified ELES code, baselined to the NERVA 75,000 lb_f thrust engine. A range of thrust levels from 15,000 to 250,000 lb_f; a range of fuel types - graphite (2200-2500 K), composite (2500-2900 K), and carbide (2900-3300 K); chamber pressures of 500 and 1000 psia, and an expander cycle baseline engine, were studied. A maximum thrust/weight of 5.5 was reached with a 1000 psia chamber pressure and 2500 K graphite fuel. Higher temperature composites and carbides had lower thrust/weight, because of the higher density of the fuel. More work will be conducted in 1992 to complete these comparisons for other concepts.

INTERACTIONS WITH OTHER PANELS

Five other panels were also at work in 1991, addressing other nuclear propulsion issues:

- mission analysis,
- nuclear safety policy,
- fuels and materials technology,
- nuclear electric propulsion technology, and
- test facilities.

Since many of these issues are closely related, the panels worked closely together, with frequent and regular interchanges of information. The panel chairmen met regularly for coordination. In some cases recommendations were the result of joint sub-panels

from more than one panel. Some of these recommendations are discussed in this report. For example, a reference "all-up" manned mission to Mars was used to establish NTP performance requirements for use by the facilities panel to estimate major facility requirements. The mission data was provided by the Mission Analysis Panel, and the associated NTP technology requirements were provided by the NTP Technology Panel.

NUCLEAR FUELS TECHNOLOGY

There was considerable interchange between the NTP Technology Panel and the Fuels and Materials Technology Panel that led to a recommended, evolutionary NTP fuels strategy. The strategy includes three difference fuel classes (NERVA-derived thermal reactor fuel, carbide particle fuel, and cermet fuels), ranked in priority order, respectively. The initial target exit gas temperature for the project will be about 2700 K (with appropriate safety and design margins). As higher temperature fuels are developed and validated, they would be incorporated into reference system designs. Development of each of the fuel types would follow a similar test sequence. Initial efforts would focus on fabrication techniques and property measurements. Hot hydrogen coupon tests would be conducted to measure erosion and corrosion rates in a non-nuclear test. Next, a nuclear test with hot hydrogen would be conducted to establish a database for fission fragment release, life and corrosion rate as a function of temperature. This data should permit a selection of fuel form or forms to meet fission fragment release requirements. Next, the fuels would be made into (sub-scale) fuel element configurations, for electric heating tests (coating integrity, cooling performance, and so forth). Full fuel elements would then be tested in an experimental nuclear reactor, in a hot hydrogen environment. Finally, full scale reactor and engine tests are planned to verify technology readiness.

NON-NUCLEAR TECHNOLOGIES

The current state-of-the-art was reviewed, and NTP technology test plans are presented for other technologies required for an NTP system:

Nozzles: Regeneratively-cooled nozzle technology has progressed significantly since the NERVA program. The space shuttle main engine (SSME) currently operates at greater than 3100 K, with heat flux about four times the NERVA nozzle. Uncooled carbon composite nozzle extensions (up to 500:1 area ratio and 14 feet diameter) will require significant technology development and validation, however. The interface between the cooled nozzle and the uncooled nozzle extension is expected to be a significant challenge.

Propellant Feed Systems: Similarly, turbopump technology has also progressed. The SSME turbopump operates at 3000-7000 psia. Carbon composite rotor blades have been proposed for some advanced concepts, but will require considerable development. Significant advances have also been made with double-redundant valving and feed system controls.

Conceptual designs: Several concepts with advanced cooling configurations have been proposed; feasibility issues remain and must be overcome before they can become serious contenders for the SEI missions.

Instrumentation/controls: One of the major challenges will be to develop autonomous instrumentation, controls, and health management software and hardware to permit the NTP engine to "fly" itself. While the manned missions are very important, the system must first serve on the cargo or scientific missions - completely unattended. Because of communications delays from earth to the spacecraft on route to Mars, the system must be capable of detecting anomalies and taking appropriate actions. In addition, no reliable techniques exist to measure surface temperatures above 2600 K for extended periods. Accurate measurements of exhaust velocities and temperature, fission product content, and particulate content will be required for both ground-based testing and space-based operation.

CONCURRENT ENGINEERING

The NTP panel recommends a "concurrent engineering" approach for the nuclear thermal rocket (NTR) technology development and "Advanced Development". This includes an "Authority to Proceed" in about 1998 for initiation of the flight hardware design, in parallel with ground testing and technology validation. This would permit a first flight of an NTR system in 2008 or earlier, followed by frequent cargo and manned lunar missions. A cargo mission to Mars is envisioned in late 2011, followed by the first manned mission in 2014.

"FAST TRACK" OPTION

It was noted at the NTP workshop in 1990 that a nearer-term NTR engine development option exists, that would utilize up-graded NERVA technology, to have a nuclear engine for first flight by about 2000-2005. The NTP panel agreed that a NERVA-derived system probably could be developed in that time period, if an "Authority-to-Proceed" were granted early, and adequate development funding were provided. The ground test facility would probably continue to be the pacing item in the development schedule, but existing experimental reactor facilities (e.g., the LOFT facility at INEL), may be adaptable to conduct ground testing, perhaps at lower power levels. Similarly, if the Air Force builds a ground test facility

for their recently unclassified SNTP program, it may be possible to modify it to meet SEI testing requirements. A separate "Fuel Element Tester" would probably not be required for NDR fuel element testing, since the power densities in the existing ATR experimental reactor at INEL, or other existing facilities, would be adequate to test NDR fuel element clusters.

The total cost of developing a near-term NTR engine would probably be less than the technology development program described as the baseline in this report, as a result of the significant reduction in the scope of the project. The system performance would probably be less: specific impulse of 800-850 seconds, instead of 925 seconds, and the technical risk would certainly be higher, since only one concept would be developed. The "Fast Track" approach would focus only on the NERVA reactor concept, updated with advanced graphite, improved coatings and/or composite fuels. This near-term option will be studied further in the months ahead.

ACKNOWLEDGMENTS

The Interagency NTP Technology Panel has been very useful to the NASA Nuclear Propulsion Office in FY 1991. Their efforts have added clarity to the draft technology development plans, and they have helped to identify and resolve critical issues. Their efforts are sincerely appreciated.

1.0 INTRODUCTION

The NASA Lewis Research Center was selected to lead nuclear propulsion technology development for NASA. Also participating in the project are staff from the NASA Marshall Spaceflight Center and the Jet Propulsion Laboratory. The U.S. Department of Energy is also an active participant and will develop nuclear technology for the project and will conduct nuclear testing at appropriate DOE test facilities. NASA program management is the responsibility of Dr. Gary Bennett of NASA/RP. The project includes both nuclear electric propulsion (NEP) and nuclear thermal propulsion (NTP) technology development.

This report summarizes the efforts of an Interagency panel that evaluated NTP technology in 1991. Other panels were also at work in 1991 on other aspects of nuclear propulsion, and the six panels worked closely together. The charters for the other panels and some of their results are also discussed. Important collaborative efforts with the other panels are highlighted.

The Nuclear Propulsion Office at the NASA Lewis Research Center prepared a draft Nuclear Propulsion Project Plan in response to a "Nuclear Propulsion Technology Thrust Plan" for the Space Exploration Initiative (SEI) prepared by NASA Headquarters Office of Aeronautics and Space Technology. The nuclear propulsion technology development project will be guided by SEI mission requirements as they are defined by NASA SEI planners at the Exploration Program Office (EXPO) at Johnson Space Center and Headquarters Code X. These mission requirements will remain a "moving target" for some time as SEI studies continue and the mission architecture is selected (see Fig. 1). The NTP Technology Panel started its deliberations with a detailed review of the NASA draft Nuclear Propulsion Project Plan.

The draft project plan includes an iterative, parallel, systems engineering and conceptual design phase and an "enabling" technology development phase, followed by extensive system testing to verify technology readiness. This project is currently planned to develop the technology to "technology readiness level 6" -(TRL-6), full system ground testing complete by 2006, validating technology readiness.

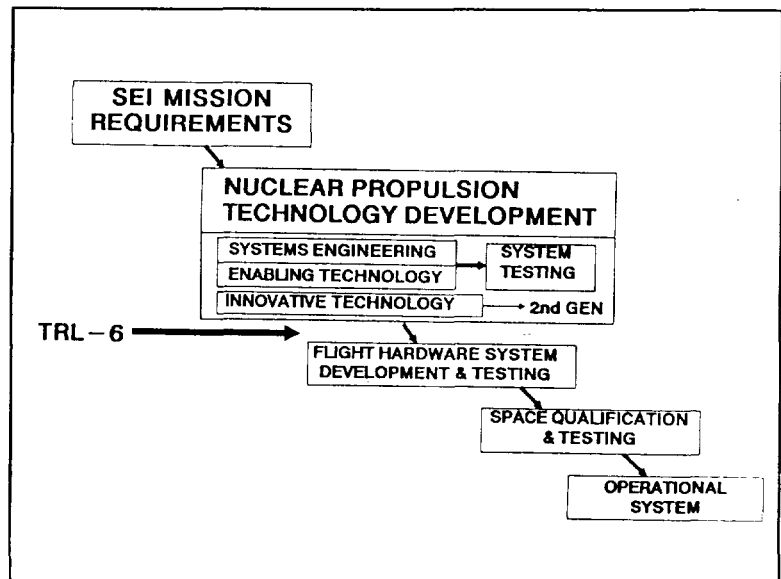


Figure 1 NTP Project Overview

It should be noted that flight hardware system development and testing, and space qualification and testing, are currently not included in the draft project plan at this time, but must be conducted before a nuclear rocket system will be ready for operational status. It is also recognized that in order to reach TRL-6 by 2006, and be ready for a first flight of a nuclear system by 2008 (or earlier), the technology development and flight hardware advanced development and flight qualification must be conducted in parallel. Decisions on mission architectures and flight dates will strongly affect this approach, and are expected to be required relatively early in the technology development project.

Innovative technology development is also included in the project because of the potential for significantly higher performance and, hence, reduced trip times and exposure of the astronauts to intergalactic cosmic radiation.

Section 2.0 that follows describes the background planning activities that resulted in the formation of the panels in 1991, and provides an overview of their activities. Section 3.0 provides a brief summary of the NTP concepts considered during the panel deliberations, and Section 4.0 describes in detail the 1991 panel activities, results, and technology state-of-the-art summaries. Section 5.0 is a summary of the major results, and 7.0 provides an extensive reference list.

2.0 BACKGROUND

2.1 FY 1990 ACTIVITIES

Studies of nuclear propulsion mission benefits have been conducted at the Lewis Research Center for several years (Ref. 1-8). Nuclear propulsion was considered by the 90-day Study team in 1989, but the study team recommended a chemical/aerobrake system as the baseline for the manned Mars mission; nuclear propulsion was recognized for performance advantages, but was relegated a backup role (Ref. 9-10). In early 1990, Lewis was charged with preparing a project plan for nuclear propulsion technology.

As a result, the Nuclear Propulsion Office (NPO) at NASA-Lewis was formed in 1991, and the NASA Nuclear Propulsion Technology Project was initiated. A draft project plan was prepared (see Ref. 11) that was responsive to the NASA/RP Nuclear Propulsion Technology Thrust Plan and included:

- Phase I: Parallel concept definition, conceptual design and enabling technology development through 1996
- Phase II: Preliminary and detailed design, and component and sub-system technology development to permit selection of a concept(s) for flight-qualification testing by 2001

Phase III: Full system technology validation via ground testing

The nuclear propulsion technology draft plan includes technology development for both NTP systems and NEP systems. Both are candidates for a wide range of NASA missions associated with SEI and other scientific missions. No choice between the two systems for SEI missions has been made by NASA at this time. Similar planning by the NEP technology panel will be discussed later in this report.

2.1.1 NTP WORKSHOP

Workshops were held in June, 1990 in Pasadena, CA on nuclear electric propulsion and in July, 1990 in Cleveland, OH on nuclear thermal propulsion technologies, (Ref. 12-15). Panels of technical experts were assembled at the workshop to assess the concepts and technologies presented based on:

- mission benefit (performance)
- safety
- technology plans and technical risk
- development schedule and estimated cost

The workshops were held early in the project planning phase to identify those activities that should be initiated in FY 1991, and provide a first order estimate of the technology requirements and development costs associated with the project.

2.1.1.1 Purpose

The Nuclear Thermal Propulsion workshop was planned to provide the following important input to the Nuclear Propulsion Project Plan:

- (1) a first-cut estimate of the performance of competing nuclear thermal propulsion concepts for a piloted mission to Mars;
- (2) a database of the technology state-of-the-art for each of the competing concepts, and key critical tests that must be successfully completed to adequately verify the technology readiness;
- (3) initial estimates of test requirements, facility requirements, test schedules, milestones, and a first-order estimate of development costs to develop the technology for one or more nuclear propulsion systems qualified and ready for initial flight test by 2006. Current project planning milestones call for the initial NTR flight in about 2008.

Many nuclear thermal propulsion concepts were presented at the NTP workshop; Table I summarizes the concepts, (Ref. 15). The table lists the concepts presented, the concept presenter and his affiliation, and

Table I Summary of Concepts Presented at The NTP Workshop

CONCEPT:	CO./CFP	TRL	PERFORMANCE PARAMETERS				
			Isp (Sec)	TRIP TIME, (DAYS)	IMLEO, (Klb)	FUEL	TEMP. (K)
SOLID CORE:							
NERVA BASELINE*	---	6	825-850	434	884	DUPLEX	2270
ENABLER	W/FARBMAN	4-5	925-1080		713	UC-ZrC-C	2700-3300
CERMET*	GE/KRUGER	4-5	832			UO ₂ /W	-
WIRE CORE	RI/HARTY	2	930			UN/W	3030
ADV. DUMBO	LANL/KIRK	3-4	-			UC/ZrC	2700-3300
PELLET BED	NM/EL-GENK	3	998			UC/TaC	3100
PARTICLE BED	BNL/LUDEWIG	4	1000-1200	434	660	UC/ZrC	3000-3500
LOW PRESSURE	INEL/RAMS.	1-2	1050-1210		814-534	UC/ZrC	3000-3600
FOIL REACTOR	SNL/WRIGHT	1-2	990		992	UO ₂	2700/3400
LIQUID CORE:							
LIQUID ANNULUS	BNL/LUDEWIG	1	1600-2000			?	3000-5000
DROPLET CORE	FL/ANGHAIE	1-2	1500-3000	<200	600	?	5000-7000
GASEOUS CORE:							
OPEN CYCLE	SV/RAGSDALE	1-2	5200	60-80		U PLASMA	?
VAPOR CORE	FL/DIAZ	1-2	1280	310		UF ₄ -HfC	6000-8000
LITE BULB	UTRC/LATHAM	1-2	1870			?	7200
OTHER CONCEPTS:							
NIMF (@)	MM/ZUBRIN	1	283	-	50% LESS	Th/UO ₂ /Zr	2800
DUAL-MODE	+	+	+	+	+	+	+

* - 1960'S TECHNOLOGY

@ - INSITU RESOURCE UTILIZATION CONCEPT

+ - SEVERAL SPEAKERS ADDRESSED DUAL MODE CONCEPTS

the estimated "Technology Readiness Level" for the concept, and various performance parameters as presented at the workshop. The concept presenter, called a "Concept Focal Point" (CFP), was a person with background and interest in a specific concept, and was selected and invited to present the concept at the workshop. Nine solid core concepts were presented including: homogeneous thermal - NERVA (the reference concept - circa 1970), and an upgraded NERVA -ENABLER; a heterogeneous reactor - the particle bed; and fast reactors - cermet and wire core. Liquid core concepts and gaseous core concepts were also presented. A NIMF concept was presented that used in-situ propellant (CO₂), and dual mode concepts were presented. These concepts will be discussed in more detail in section 3.0 of this report.

Initial guidance was provided to each CFP to ensure that each presenter clearly understood the workshop objectives, and was prepared to answer the following important questions:

- (1) How well will the concept perform on a Piloted Mars Mission?

- (2) What is the status of the technology and what critical tests must be performed to develop the technology to flight-ready status?
- (3) Can the concept be developed to flight-ready status by 2006; what are the critical milestones; what facilities will be required; and (first-order) what will be the cost?

Panels of technical experts were invited to participate in the workshop to evaluate the strengths and weaknesses of the concepts presented in terms of safety, technical risk, performance and technology development requirements.

2.1.1.2 Recommendations

In September, 1990, the workshop technical panel chairmen summarized their recommendations for the Workshop Steering Committee. The major recommendations of the technical panels are summarized below:

Safety: The project technology development team must develop a nuclear safety culture in parallel with the technology development.

Fuels: The fuels technology development for nuclear thermal propulsion should be focussed on very high temperature (> 2500 K), relatively short life (5-10 hours) fuels, materials and coatings. The nuclear electric propulsion fuels development should be focussed on lower temperatures (1400-2000 K), but very long life (2-5 years), and relatively high fuel burnup. It was noted emphatically by the panels that these high performance goals must be balanced by "man-rating" requirements, reliability, substantial design margins, and must include significant testing to validate technology readiness.

Systems Engineering: A strong concept development and systems engineering effort must be included in the project that includes:

- consistent conceptual design studies and comparisons
- requirements definition and control
- preliminary and detailed hardware design
- sub-system and full system test verification

Facilities: Since major ground test facilities are expected to be a long lead time (and high cost) part of the project, initial studies and long lead time activities should be initiated as soon as possible. For nuclear thermal propulsion (NTP), a "nuclear furnace" will probably be required to test full size fuel elements in a relevant nuclear environment and applicable power density levels, and a full system ground test facility with full effluent cleanup will be required to demonstrate TRL-6.

Other Technologies: Other technologies are at relatively lower priority early in the project. For example, for NTP, nozzle and feed

system technologies have been developed extensively for the space shuttle main engine (SSME), and will not require "break through" technologies for the NTP system. Instrumentation, controls, diagnostics and health monitoring will be important technology development activities and should be included from the start in the conceptual design activities and in the development of high temperature instrumentation technology. Then, as the concepts evolve and become defined more clearly, the technology development can focus on high payoff efforts.

Innovative Technologies: Technologies that can lead to substantial improvements in transit times for the astronauts should be included in the project. Initially these efforts should focus on the "proof-of-concept" experiments and analyses that will be required to verify the viability of the concept.

Public Acceptance: It was recommended that a proactive public perception, public acceptance program be included as an integral part of the project.

Cost Estimates: The cost of the technology development program was estimated by consensus of the panels to be (rough order of magnitude) between two and five billion dollars. However, there was much uncertainty in these estimates and general consensus that the estimates would require much more study.

2.1.2 1990 STEERING COMMITTEE RECOMMENDATIONS

The nuclear propulsion workshop steering committee (Dr. Gary Bennett, NASA/RP, Earl Wahlquist, DOE/NE, and Lt. Col. Roger Lenard, AFPL) reviewed the results of the workshops, and recommended a continuation of the interagency planning efforts. "Ex Officio" members of the Steering committee included Dr. Franklin Chang-Diaz, a NASA astronaut, and managers from NASA Centers, DOE laboratories and the Department of Defense. Tom Miller of NASA-Lewis was Executive Secretary of the Steering Committee.

2.1.3 INDUSTRY FEEDBACK MEETING

Summaries of the concepts, the workshop panel recommendations, and the steering committee recommendations were presented to industry and academia at a feedback meeting on November 15, 1990 in Houston, Texas. A number of issues were identified at this meeting and Dr. Bennett recommended the continuation of the "technical panel" activities to address a number of these issues. At this meeting, Dr. Bennett invited industry and university representatives to participate in these panels as "industry observers" to maintain the industry interest and to maintain the momentum of the planning activities in 1991.

2.2 FY 1991 PANEL ACTIVITIES

As a result, the six interagency technical panels were formed in 1991

to address the key issues identified at the workshops and by the Steering Committee and to continue to refine the technology project plans. Each of the panel chairmen presented a summary of their results at the AIAA/NASA/OAI Conference on Advanced SEI Technologies in Cleveland in September, 1991. The panel charters and results will be summarized in the next section of this report, and important interactions between panels will be discussed.

2.2.1 CHARTER/ISSUES

2.2.1.1 Mission Analysis Panel

The mission analysis panel was chartered to provide consistent mission performance data and studies to permit a fair comparison between the various nuclear propulsion concepts proposed. Reference missions were selected early in FY 1991 to focus the technology requirements and enable the early definition of facility requirements. The reference missions used to estimate major test facility requirements are summarized in Table II (Ref. 16). For both NEP and NTP systems an "all-

Table II Reference Missions Led to Facility Requirements

<u>NTP</u>	<u>NEP</u>
<ul style="list-style-type: none"> - "all-up" mission - (3) perigee burn - (3) engine cluster 75,000 lb thrust each - 1 1/2 hrs. total burn time - 1/2 hr. max. single burn - (8) Restarts/mission - 2700 K exhaust temp. with appropriate safety & reliability margins - 925 seconds Isp 	<ul style="list-style-type: none"> - "all-up" manned mission - multiple missions (reusable) refurbish thrusters, replace propellant - 10 MWe power - 10 kg/kWe - 400 mt IMLEO (2016) - 250-300 days one-way transit - 500-600 days opposition-class mission - "split" missions → 400 days R.T. - cargo → minimum energy

up" manned mission to Mars in 2016 was assumed. Subsequently, the Stafford Synthesis Group Report has recommended "split-sprint" manned missions to Mars starting in 2014 (Ref. 17). This mission has been studied extensively by the members of the Mission Analysis panel, including the effect of engine-out on mission abort scenarios (Ref. 18). The panel also studied performance tradeoffs associated with:

- specific impulse and thrust-to-weight ratios
- crew size

- opposition-class missions and conjunction-class missions
- nuclear heating of system components
- cooldown propellant requirements
- engine clustering effects

Quantified Figures-of-Merit (FOM) were identified and a structure developed to evaluate and compare competing systems; much work remains to complete this evaluation, however (Ref. 19).

2.2.1.2 Nuclear Safety Policy Working Group

A joint interagency Nuclear Safety Policy Working Group was formed to develop the basis for a policy on nuclear propulsion safety, (Ref. 20,21). Existing U.S. safety policies, DOE orders and directives were reviewed, and the following recommended policy statement has been proposed:

"Ensuring safety is a paramount objective of the Space Exploration Initiative nuclear propulsion program; all program activities shall be conducted in a manner to achieve this objective. Stringent design and operational safety requirements shall be established and met for all program activities to ensure the protection of individuals and the environment. These requirements shall be based on applicable regulations, standards, and research. The fundamental program safety philosophy shall be to reduce risk to levels as low as reasonably achievable."

A comprehensive safety program shall be established. It shall include continual monitoring and evaluation of safety performance and shall provide for independent safety oversight. Clear lines of authority, responsibility, and communication shall be established and maintained. Furthermore, program management shall foster a safety consciousness among all program participants and throughout all aspects of the nuclear propulsion program."

Several program safety requirements are proposed, including: (1) reactors shall remain subcritical prior to the system achieving earth orbit (except for zero power testing on the ground), (2) risk identification and reduction efforts shall be included in the program, and probabilistic goals shall be demonstrated through testing and analysis, (3) the return of used (radioactive) reactors shall not be a planned mission event, and the probability of accidental reentry shall be made as low as practical (the reactor must be designed to remain subcritical during any accidental entry and impact), and (4) adequate disposal of spent reactor subsystems shall be explicitly included in the mission planning and design activities.

The working group also made several recommendations to further enhance mission safety. These included specific recommendations regarding:

- radioactive release under normal operating conditions
- radioactive release under accident conditions

- safety validation testing
- launch safety
- powered flight safety
- ground test and equipment safety
- special nuclear materials safeguards

2.2.1.3 Fuels/Materials Technology Panel

This panel was chartered to define a fuels and materials technology program for both NTP and NEP reactor systems (Ref. 22,23). An early output from this panel described facility requirements for nuclear fuel testing. Detailed test objectives were defined for a wide range of possible fuel types (reactor types). The initial fuels test program includes fuel fabrication and production development, measurement of fuel properties for design and evaluation, fuel concept screening in relevant temperature, fluid and nuclear environments, and development of adequate materials properties data for safety and reliability analysis.

An assessment was made of the potential commonality between NTP and NEP fuel types. The assumed requirements for NTP reactors included:

- operating temperatures from 2500 to 3600 K
- engine operating time per mission, less than 10 hours
- low fuel burnup (hence, low fission fragment inventory)
- reactor power from 1000 to 5000 MW_{th}

For NEP reactors the assumed requirements included:

- temperatures from 1350 to 2000 K
- reactor operating lifetime, up to 7 years
- high fuel burnup (hence, high fission fragment inventories)
- reactor power 25 to 100 MW_{th} (5 to 10 MW_e)

Thus, NTP and NEP fuel commonality appears to be relatively limited. Gas cooled NEP reactors could utilize prismatic or particle fuels developed for NTP, provided adequate provision is included for the longer life and higher fission fragment buildup in the fuels.

2.2.1.4 Nuclear Electric Propulsion Technology Panel

The NEP Technology Panel was chartered to characterize NEP system options, including integrated reactor and thruster interactions, using common, consistent ground rules and assumptions, and to develop an NEP technology development plan (Ref. 24). Five major sub-systems usually make up an NEP system: reactor, power conversion, thermal management, power management and distribution (PMAD), and thruster. Many component options have been identified that could be used to make up the NEP system, but an "optimized" system has not been designed, nor is the technology in hand for a manned NEP mission to Mars. A conceptual design study is proposed early in the program to focus on an optimized system design, and to help focus the technology development activities.

The NEP technology development plan is evolutionary, in that it contains interim milestones and missions to verify the technology readiness in low-power, interplanetary mission applications first, and then progressing to the more challenging Mars cargo and piloted missions (Ref. 25). The NEP technology development plan is highly integrated with the existing NASA/DOE/DoD SP-100 space reactor program and the SP-100 technology is an effective "jumping off" point from which the NEP systems may be developed.

The major NEP technical challenges include:

- high power, high temperature reactors, turbines and radiators
- high burnup fuels and reactor designs
- efficient, high temperature power conditioning
- high efficiency, long life thrusters
- effective integration of the NEP components

The high system specific impulse, however, makes the system ideally suited for long missions where minimum propellant usage is critical.

2.2.1.5 Test Facilities Panel

The Test Facilities Panel was chartered to identify nuclear propulsion test facility requirements and options early in the panel deliberations, since major facilities are believed to be long-lead-time elements of a test program (Ref. 26-28). Reference mission requirements were provided by the Mission Analysis Panel, and test requirements were provided by the NTP, NEP, and Fuels/Materials Panels. A number of potential test sites were visited, and a significant database was established for facilities that may be used in the technology development project (Ref. 29).

Major new NTP test facilities will pace the technology development and will probably include an NTP fuel element tester (nuclear furnace) capable of testing a wide range of element concepts, and an NTP system ground test facility with multiple cells for reactor and engine tests and flight system engine qualification tests. The NTP test facilities will include full effluent cooldown and cleanup to ensure environmental compliance. It was estimated that the earliest that a nuclear furnace facility could be completed is 1997, and the full system ground test could be available in 1999.

2.2.1.6 Nuclear Thermal Propulsion Technology Panel

This report summarizes the results and recommendations of the NTP Technology Panel. The NTP Technology Panel was chartered to evaluate nuclear thermal propulsion concepts on a consistent basis, and to continue technology development project planning for a joint technology development project in nuclear propulsion for the Space Exploration Initiative (Ref. 30). Concepts were categorized based on probable technology readiness date, and innovative concept "proof-of-concept" tests and analyses were defined. Further studies will be required to

provide a consistent comparison of all of the NTP concepts (Ref. 31).

The NTP panel agreed that the highest priority technology development efforts should be (1) high temperature fuels and materials development, (2) long lead time facilities design and construction for technology validation testing, and (3) conceptual design studies to focus the technology development efforts. Instrumentation development, neutronics, controls, health management and diagnostics system integration will also be very important and should be included in the project from the beginning.

2.2.2 1991 STEERING COMMITTEE MEETING

The 1991 Steering Committee meeting was held on May 2, 1991 at the Lewis Research Center. The actions assigned to the NTP panel are paraphrased here and discussed in depth in Section 4.0:

- (1) Identify NTP concepts that could be developed to TRL-6 by 2006.
- (2) Brainstorm criteria for concept selection and discuss with Mission Analysis Panel.
- (3) Conduct a high temperature materials workshop.
- (4) Develop plans for completing panel activities in 1991, including the final panel reports.
- (5) Define key programmatic and technical milestones for FY 1992.
- (6) Raise "Figures-of-Merit" blending discussions to mission planners.
- (7) Review recommendations of 1990 workshops.
- (8) Incorporate safety policy statement in technology plans.
- (9) Define evolutionary fuels strategy and performance goals.
- (10) Review test facility requirements and identify test conditions required for various reactor types.
- (11) Identify concept-specific safety issues.

On June 11-13, 1991, several panels met at the Idaho National Engineering Laboratory (INEL) to respond to the steering committee actions; the issues that were addressed by the NTP Panel are discussed in detail in Section 4.0 and 5.0 of this report.

2.2.3 COORDINATION BETWEEN PANELS

It was recognized early in the panel planning activities that significant coordination would be required between the various panels.

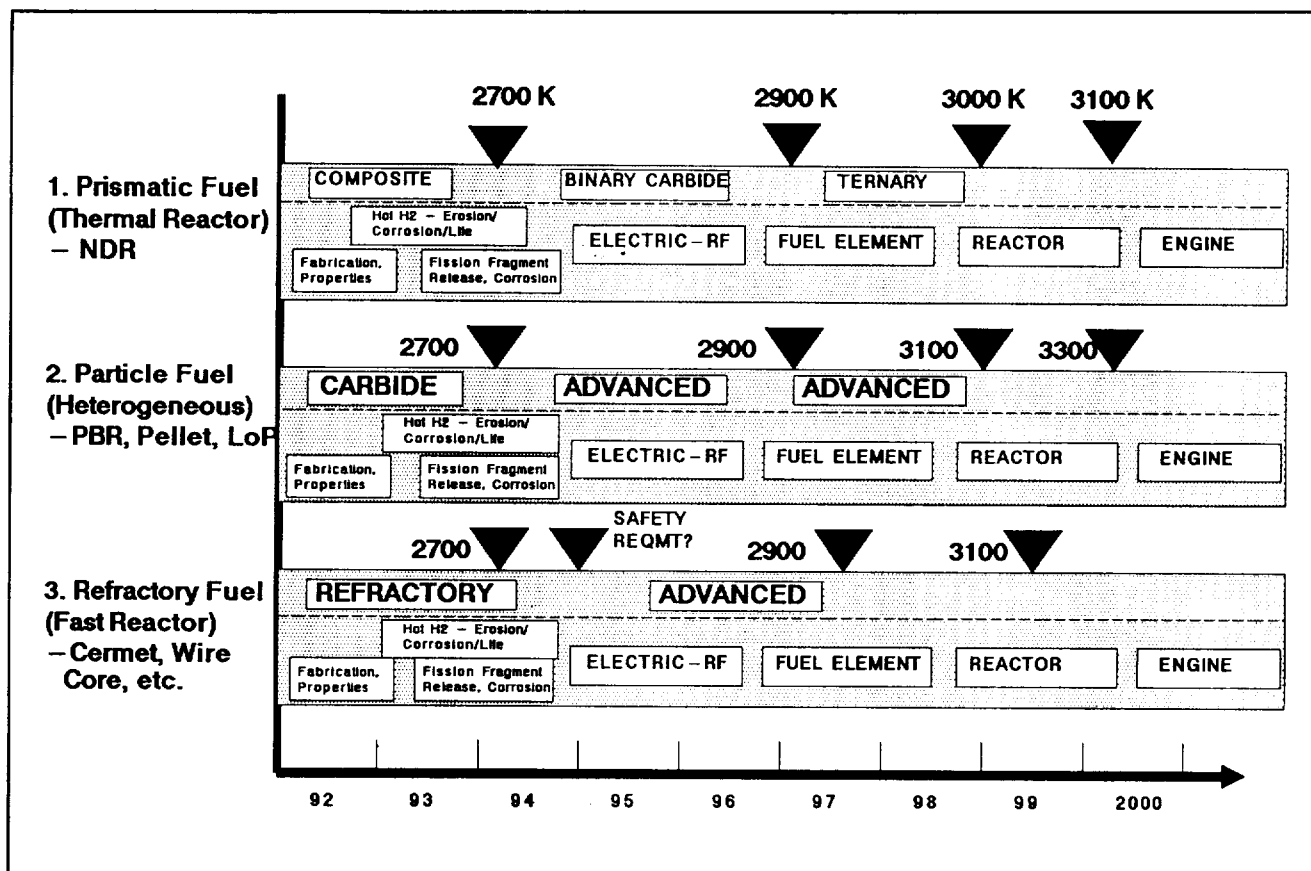


Figure 3 NTP Evolutionary Fuels Strategy

three different fuel classes, ranked in priority order from top to bottom in the figure.

For NTP, a composite prismatic fuel for a thermal reactor (typical of the NERVA/ROVER concepts tested in the 1960s and early 1970s) is the top priority because of the extensive database that exists for this concept. Particle fuels may offer performance potential, but this potential performance advantage must be verified. Similarly, cermet fuels may offer fission fragment retention advantages, and may also have high performance (Ref. 31).

The initial target exit gas temperature for the NTP system will be about 2700 K (with appropriate safety and design margins), with composite fuels. As higher temperature fuels are developed and validated, they will be incorporated into reference system designs.

Each of the fuel classes will follow a similar test sequence as indicated on figure 3. Initial efforts will focus on fabrication techniques and property measurements for fuels and coatings. Hot hydrogen coupon tests will be conducted to measure erosion and corrosion rates in a non-nuclear test. Next, a nuclear test with hot hydrogen will be conducted to establish a database for fission fragment release,

life and corrosion rate as a function of temperature. This data should provide a basis for selection of fission fragment release requirements. This data is required to define ALARA (as low as reasonably achievable) for fission fragment release requirements.

The fuels will be made into fuel element configurations, for electric or RF heating tests, to evaluate coating integrity and cooling performance. Full fuel elements will be tested in a nuclear, hot hydrogen environment in either an existing experimental reactor or a new "nuclear furnace"-type element tester. Finally, full scale reactor and engine tests are planned to verify fuel element technology readiness.

The remaining sections of this report will focus on the results and recommendations of the NTP Technology Panel, and will include a discussion of the issues raised by the steering committee. Section 3.0 presents a review of NTP concepts; Section 4.0 presents a detailed summary of the results of the panel deliberations; and section 5.0 discusses the results.

3.0 NTP CONCEPT SUMMARIES

This section summarizes the concepts presented at the NTP Workshop in July, 1990 (Ref. 15). These concepts were summarized earlier in Table I. Table I lists all of the Nuclear Thermal Rocket (NTR) concepts that were presented at the NTP Workshop, as well as Concept Focal Point (CFP) and his affiliation. Also, several concepts are shown (#) that were not presented at the workshop, but will be discussed briefly.

The Performance Parameters, Time to TRL-6 and Cost to TRL-6 shown were presented by the CFP, and show a wide range of differing assumptions. In many cases no estimates were attempted for the performance for the baseline Mars mission, and old data (*) were presented, with a discussion of the improvements that might be made to the concept if improved technologies were included.

The concepts are grouped with similar concepts: Solid Core, Liquid Core, Gaseous Core, and Others. The NERVA baseline is shown first in the Table, and the performance parameters are indicated for the baseline manned Mars mission were specified to the CFPs.

The following sections present and discuss each of these concepts, and addresses some of the technology issues associated with each concept (see Ref. 15 for more details).

3.1 SOLID CORE REACTORS

Nine solid core reactor concepts were presented at the workshop. A brief discussion of the Tungsten Water-Moderated Reactor concept is also included.

3.1.1 ROVER/NERVA BASELINE

The ROVER/NERVA reactor system was used as a baseline or "reference engine" system at the workshop (Fig. 4). A Baseline Nuclear Thermal

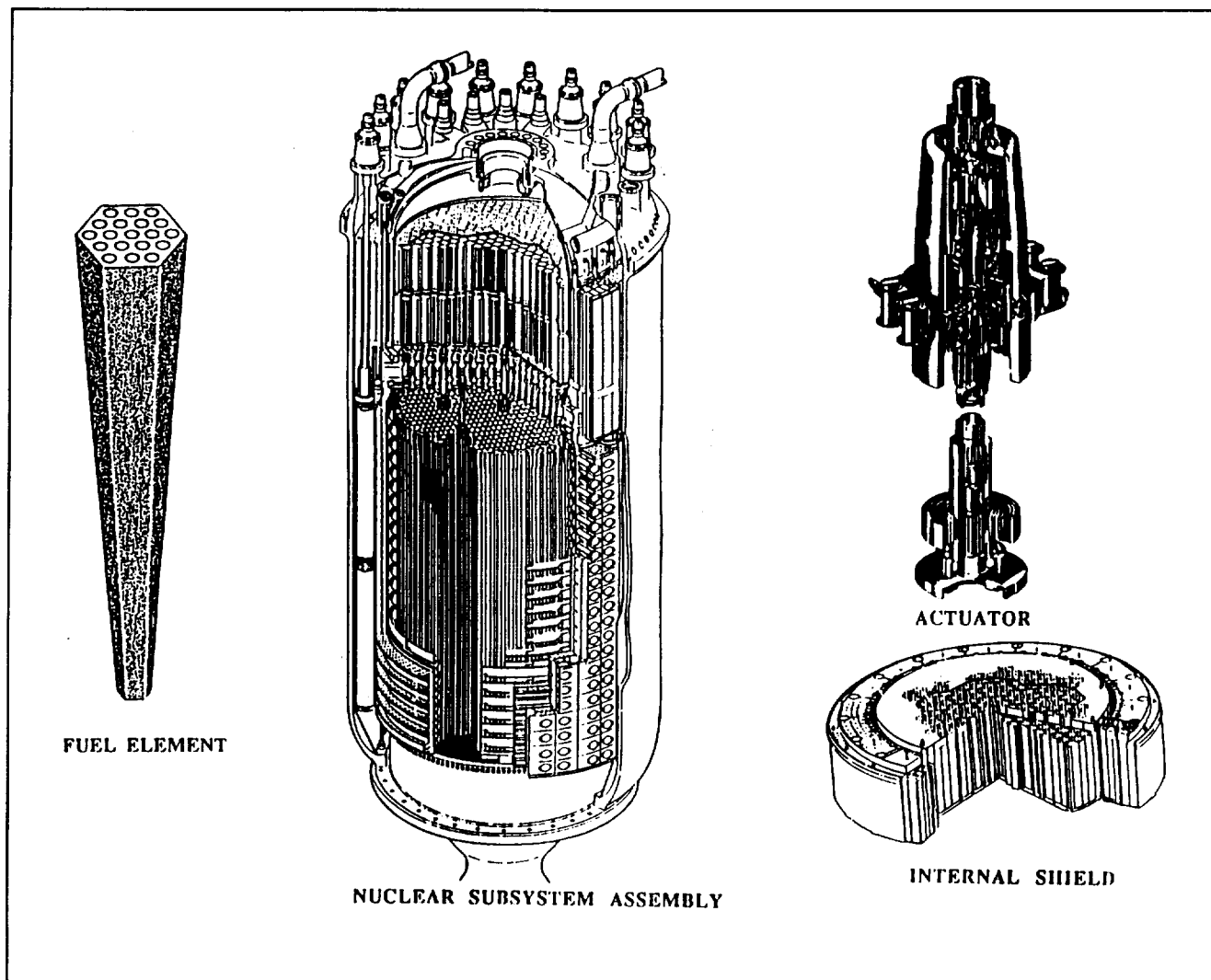


Figure 4 ROVER/NERVA Reactor Core

Rocket Mission, using the ROVER/NERVA engine, was described to the CFP, and was to be used for comparison with other concepts. The reference mission described was a "full-up" (rather than a "split-sprint"), piloted Mars mission aimed at a launch opportunity in 2016, with a 30-day stay on Mars (opposition class), vehicle assembly and initial reactor startup in Low Earth Orbit (LEO) - near Space Station Freedom, with estimated payloads of 124 metric tons outbound and 40 metric tons inbound. This was one of the nuclear propulsion mission scenarios that was studied extensively in the NASA 90-Day Study (Ref. 9-10). The purpose of the baseline mission was to provide a starting point for the comparisons and discussions.

A description of the baseline mission trajectory and solar geometries was also provided to the CFPs for radiation comparisons. Reactor shielding was to be included to ensure no more than 5 Rem/year from the reactor to the crew compartment, which was assumed to be 100 meters from the reactor shield. A three-perigee-burn earth escape was included, with a single baseline engine thrust of 75,000 pounds. A Venus flyby was included on the return from Mars to minimize propellant requirements. The NTR Mars Transfer Vehicle configuration was included and discussed by Borowski at the workshop (Ref. 15).

The NERVA technology was developed extensively from 1955 until 1972 when the program was discontinued. About \$1.4 billion, then-year dollars, was spent by NASA and the Atomic Energy Commission on the ROVER/NERVA program. Escalated to 1991 dollars, this equals about \$9.6 billion. The program culminated with full system ground tests at the Nuclear Rocket Development Station (NRDS) at Jackass Flats, NV, that demonstrated the required lifetimes, restartability, and performance required for the system for a mission to Mars.

A large number of excellent references exist that describe the ROVER/NERVA engine system. A few are listed here for information (Ref. 32-40).

3.1.2 NERVA-DERIVED: ENABLER

The ENABLER concept (Fig. 5) is an updated version of the NERVA baseline technology and was presented at the workshop by Farbman, formerly of the Westinghouse Corporation (Ref. 15). The fuel elements are made of a UC-ZrC-C composite matrix, approximately 2.5 centimeters hexagonal shape, about a meter long, with 19 circular coolant channels co-extruded axially. Coolant channels and external surfaces of the fuel element are coated with zirconium carbide to protect the composite fuel from the hot hydrogen. The NERVA baseline was a similar configuration, with coated fuel beads embedded in a graphite extrusion. The composite fuel was tested near the end of the NERVA program in electric furnace tests and in the nuclear furnace (Ref. 40-41). Thus, the composite fuel technology must be recaptured and demonstrated. This improved fuel should permit a chamber temperature of about 2700K, and a specific impulse (I_{sp}) of about 925 seconds. If binary carbide and/or ternary carbide fuels can be developed, it is projected that chamber temperatures may be increased to 3100 and 3300 K, respectively, with a resulting increase in specific impulse to 1020 to 1080 seconds.

The original NERVA tie tubes have been redesigned in the ENABLER concept to provide improved tie tube cooling, and to return the tie-tube coolant to the cold end of the reactor. Reintroducing the coolant to the main hydrogen flow eliminates the diluting effect of the coolant flow in the original design - improving I_{sp} even more.

An improved moderator material, Zr-H_x-C, replaces the NERVA graphite moderator. Improved safety rods are proposed to be used in place of poison wires to better control reactivity and to provide redundancy.

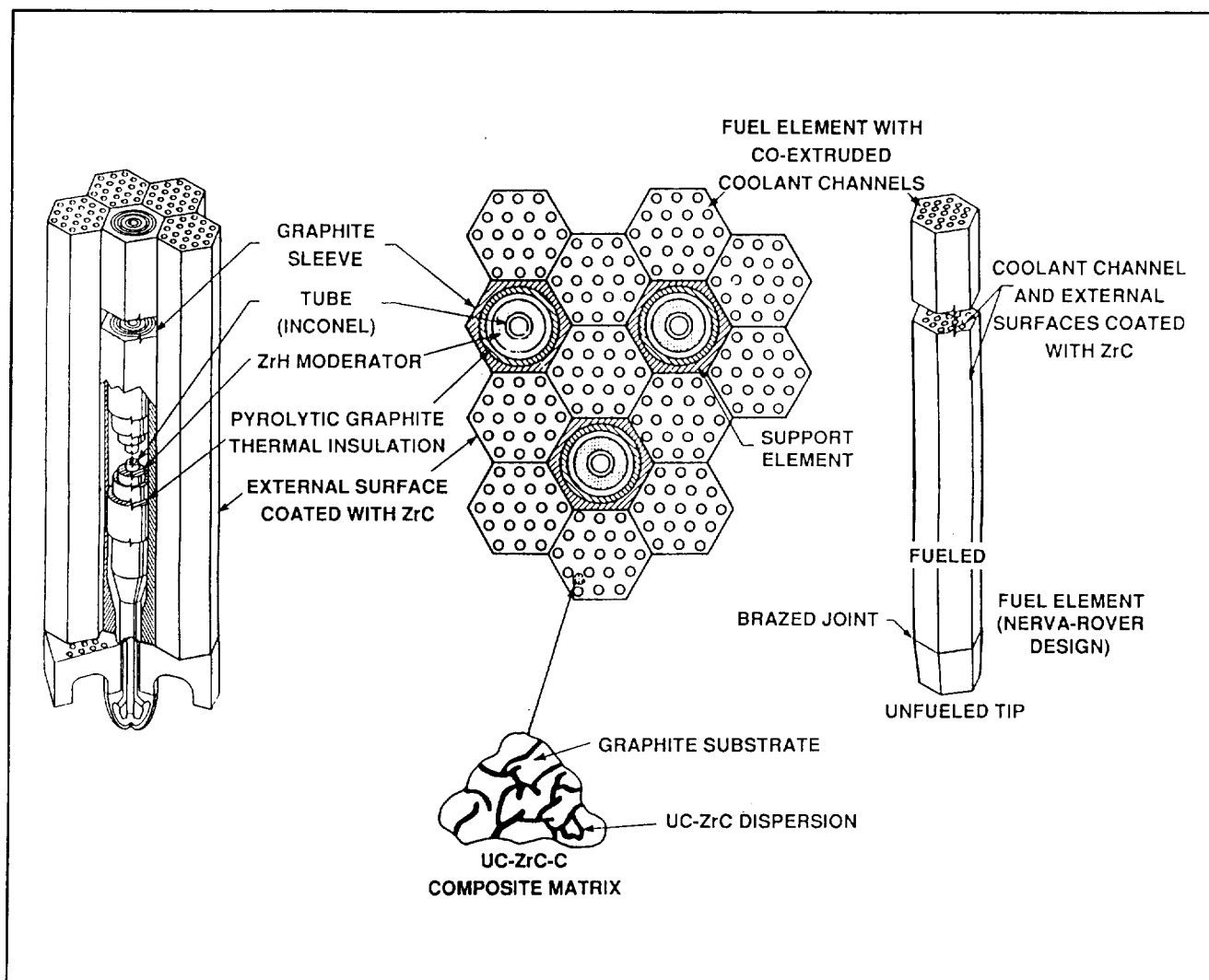


Figure 5 ENABLER Concept Fuel Elements

Electric control drives would replace the earlier pneumatic system. High strength steel will probably be required in the reactor pressure vessel to handle the higher temperatures and pressures. Nozzle chamber pressure is proposed to be increased from 450 to 1000 psia. The ENABLER composite fuel element and the new safety rod concept are both estimated to be at a Technology Readiness Level of about 4 (TRL-4). Other components are estimated to be TRL-5 or higher.

Non-nuclear ENABLER components would include significant improvements compared to NERVA technology. Turbopumps could go from 1600 psi to as high as 7000 psi (current SSME technology). Similarly, the SSME nozzle is currently operating at 3100 K and 3150 psia (21.7 MPa), compared to the NERVA design of 2500 K and 625 psi (4.3 MPa). Valves, actuators, controls and instrumentation will also be improved.

Westinghouse proposed an evolution of ENABLER technology from the earlier NERVA NRX-XE' system (tested) and a 1972 updated system design (see Fig. 6). The major change affecting specific impulse is the fuel

	NRX XE'	NERVA 72 UPDATE	COMPOSITE	BINARY CARBIDE	TERNARY CARBIDE
• Fuel	Duplex Bead	Duplex Bead/ZrC Coated	UC-ZrC-C	ZrC-UC	UC-ZrC-NbC
• Moderator	Graphite	Zr H _x /C	Zr H _x /C	Zr H _x /C	Zr H _x /C
• Reactivity Control	Drums Plus Poison Wires	Drums Plus Safety Rods	Drums Plus Safety Rods	Drums Plus Safety Rods	Drums Plus Safety Rods
• Axial Support	Tie Rod	Tie Tubes	Tie Tubes	Tie Tubes	Tie Tubes
• Control Drives	Pneumatic	Electric	Electric	Electric	Electric
• Reactor Vessel	Aluminum	High Strength Steel	High Strength Steel	High Strength Steel	High Strength Steel
• Chamber Temp (K)	2270	2500	2700	3100	3300
• Pressure (psia)	450	1000	1000	1000	1000
• Nozzle Exp. Ratio	100:1	500:1	500:1	500:1	500:1
• Isp (sec)	710	890	925	1020	1080

↑
NDR

Figure 6 ENABLER Technology Evolution

and fuel temperature for each of the evolutionary steps shown. The 1972 NERVA update design specifies an improved coating on the duplex beaded fuel and a temperature projected to 2500 K ($I_{sp} = 890$ seconds). Technical issues are believed to be minor, but include hydrogen compatibility with the coating, and possible coating cracking and fuel corrosion.

The composite UC-ZrC-C fuel is the recommended baseline for the advanced ENABLER design (NDR in Fig. 6). These fuels are a relatively modest technology stretch, but hydrogen compatibility, cracking and eutectic formation must all be tested and verified. Also, design fuel properties must be measured from fuel samples. Temperatures of about 2700 K are anticipated, with a corresponding I_{sp} of about 925 seconds. Binary carbide and ternary carbide fuels may be developed in the future and may then be used to upgrade the baseline ENABLER design. These fuels may permit improvements in both temperature and specific impulse. Very little is known about binary and ternary fuels today, however, and technical issues include: properties, melting points, hydrogen compatibility, stability, homogeneity and fabricability.

The evolutionary ENABLER approach is recommended by Westinghouse to

permit an early project start with relatively easy technology steps; improved system designs and performance capability with improved fuels may then be included when they become available.

A further enhancement in the ENABLER evolutionary technology development (called ENABLER II) has recently been proposed by Petrosky (Ref. 42), in which improved power density and heat transfer are obtained by scaling the size of the fuel elements.

The critical near-term tests that should be conducted include:

FUEL AND FUEL ELEMENTS: The technology must be demonstrated for the composite fuel to meet the temperature, lifetime, restart, and manufacturability requirements for the projected missions. This will include the ZrC coating, and coating application processes, quality assurance testing, and in-core performance and life testing.

DRUMS AND SAFETY RODS: Critical tests must be conducted to demonstrate reactor startup, control, shutdown, and cooldown capability with the redesigned system.

REACTOR SAFETY ISSUES: Full core water immersion and core compaction subcriticality issues must be addressed (for this concept and all others). The issue of intact reentry vs. breakup during reentry should be addressed early since materials and design will depend on this decision.

GROUND TEST FACILITY: Preliminary facility studies and engineering work should begin on this long lead time facility. Containment and cleanup process requirements should be studied and a policy established. Site selection and an Environmental Impact Statement (EIS) should be initiated as soon as possible because of the long lead times involved.

The ground test schedule for the ENABLER concept is estimated to be eight years, (Fig. 7) - the shortest of all of the concepts proposed at the workshop. The test facility for the full-scale test is the pacing item on the schedule and should be started immediately. This facility must be designed for exhaust collection and cleanup, and the requirements for this testing must be identified early.

The other major test facility that may be required is a nuclear fuel element testing facility. This facility will provide the capability to develop the advanced fuels required to go to the higher temperatures, and long lifetimes required for this propulsion system.

Development cost was estimated by Westinghouse to be \$0.75B to \$1.0B. Westinghouse also cautioned that this cost can be expected to increase if the program is delayed or the schedule is allowed to slip as a result of annual funding reductions. The Advanced Development Panel at the workshop estimated that the proposed estimated costs presented by all of the presenters was underestimated by a factor of at least two or three.

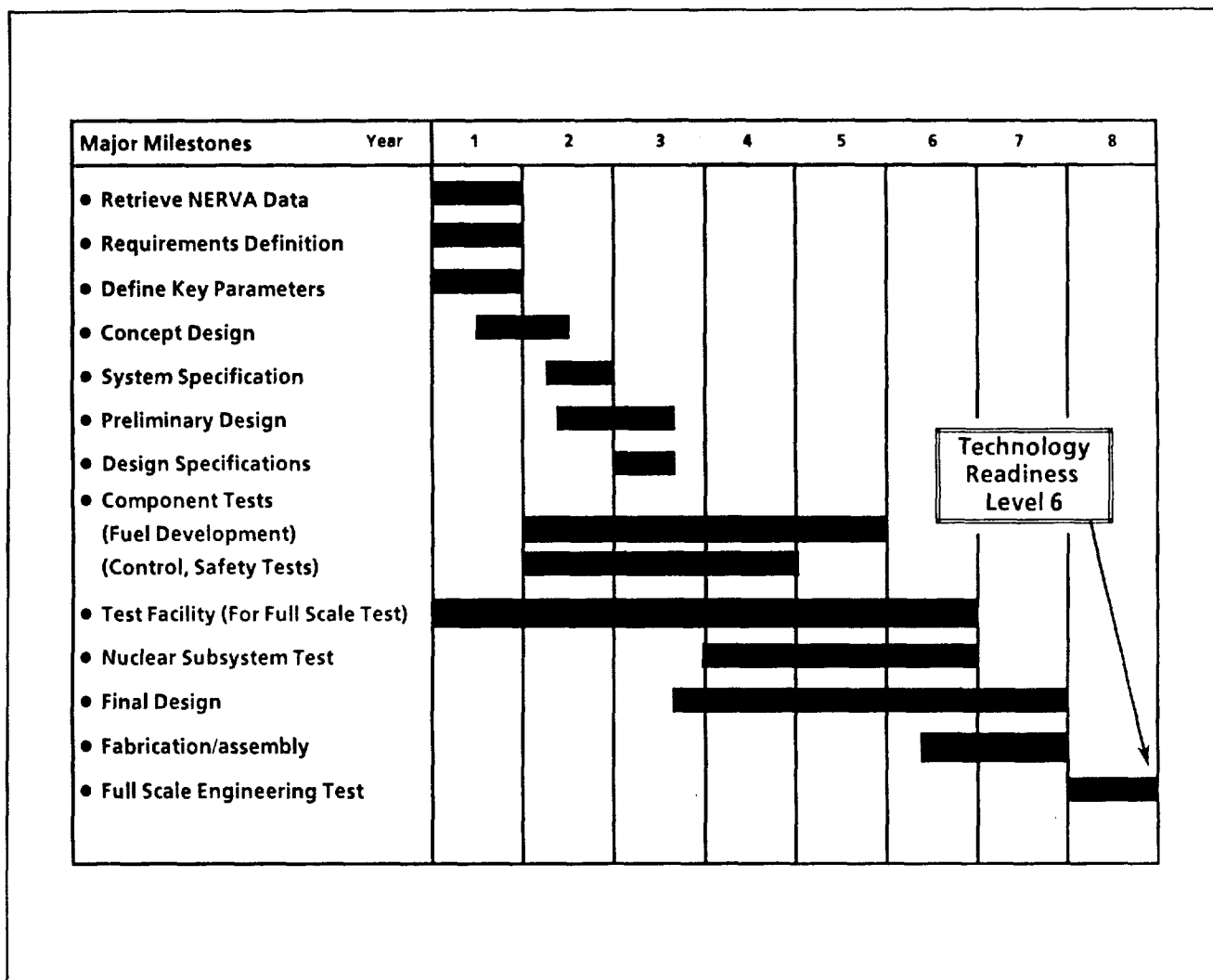


Figure 7 ENABLER Test Schedule

3.1.3 PARTICLE BED REACTOR (PBR)

The Particle Bed Reactor concept (PBR) was presented at the NTP workshop by Ludewig from Brookhaven National Laboratory (Ref. 15). This concept is shown in figure 8. Tiny fuel particles, approximately 500-700 microns in diameter, are packed between hot and cold porous cylinders, called frits. The cylindrical fuel elements and moderator assemblies are arranged in a hexagonal pattern to form the heterogeneous reactor core. Either nineteen or thirty-seven fuel elements would be used to make a reactor. A reflector may or may not be required with this reactor design. The fuel particle is formed with an inner fuel core of UC_x/ZrC , coated with porous carbon, a pyrolytic carbon, and a ZrC outer coating. The hydrogen enters the top of the core and flows down through axial passages in the moderator block. Then the hydrogen turns 90°, passes radially through the cold frit, enters the fuel particle bed where the heat generated in the particles is transferred to the

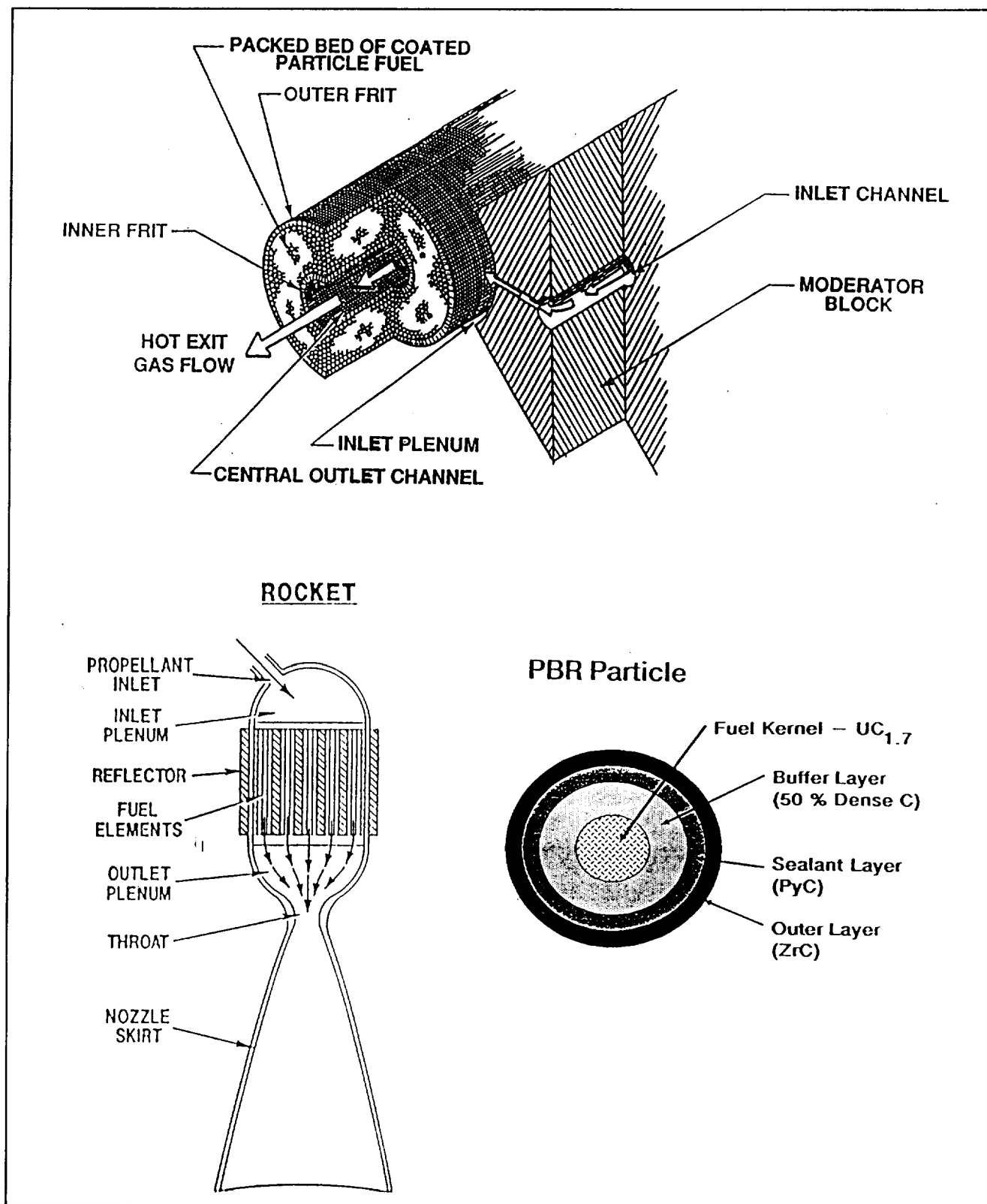


Figure 8 Particle Bed Reactor Concept

hydrogen, and finally passes through the hot frit. The hot hydrogen then exits the reactor axially to the nozzle chamber. The low moderator operating temperature makes it possible to choose a moderator which will minimize reactor size and mass for given power levels.

As a result of the very short heat transfer path in the fuel, and very high heat transfer surface-to-volume ratio of the particles, excellent heat transfer from the particles to the hydrogen is claimed. Exit temperatures were projected in the range of 3000-3750 K; specific impulse was estimated to be between 1000 and 1300 seconds (Ref. 15). The technology throughout the system is well beyond current technology levels, however, and must be validated. Control systems are located within the cooled moderator blocks.

Ludeweg claimed very high I_{sp} for the PBR concept, and because of the smaller reactor size, reduced shielding requirements. However, the feasibility of this concept has not been demonstrated. Fuel physical and thermodynamic properties must be measured, appropriate temperature margins must be determined, fuel/coating stability verified, and particle corrosion characteristics must be understood. The high surface area of the particles may in fact lead to unacceptably high carbon loss from the particle to the hydrogen propellant. Materials for the high temperature frits must also be developed. Light weight fiber-reinforced structural materials, with low neutron cross section to reduce radiation heating must be designed and tested in this environment. A variable porosity cold frit must be developed to control the hydrogen flow to the particle bed. Bed hot spots, due to laminar flow instabilities, and subsequent melting and failure must be prevented. A radiation cooled carbon-carbon nozzle must be designed for this system and other high performance systems. Carbon-carbon rotors for the turbopump assembly must be designed and verified.

Critical tests include a full size fuel element tested in a reactor at full power density levels, full temperature, and for the expected life, with appropriate man-rating margins for SEI missions. Engine conceptual designs, compatible with SEI mission requirements, should be initiated early in the project. Design of the fuel element test reactor and ground test facility, (for all the concepts), must also be started early.

3.1.4 CERMET

The prismatic CERMET reactor core concept was presented by Kruger of General Electric Corporation at the NTP workshop (Ref. 15). The concept, shown in figure 9, was developed during the 1960s for the ROVER project and the aircraft nuclear propulsion program (Ref. 43). The fuel was made up of 60 percent UO_2 and 40 volume percent tungsten, a fully enriched fuel, providing a fast spectrum reactor. The reactor described is a 1960s design at 2000 MW_t, and was not updated for the SEI reference mission. The core is about 34 inches long and 24 inches in diameter. There are 163 hexagonal shaped fuel elements, 1.87 inches across the flats, with 331 axial coolant holes, 0.067 inches in diameter. The fuel

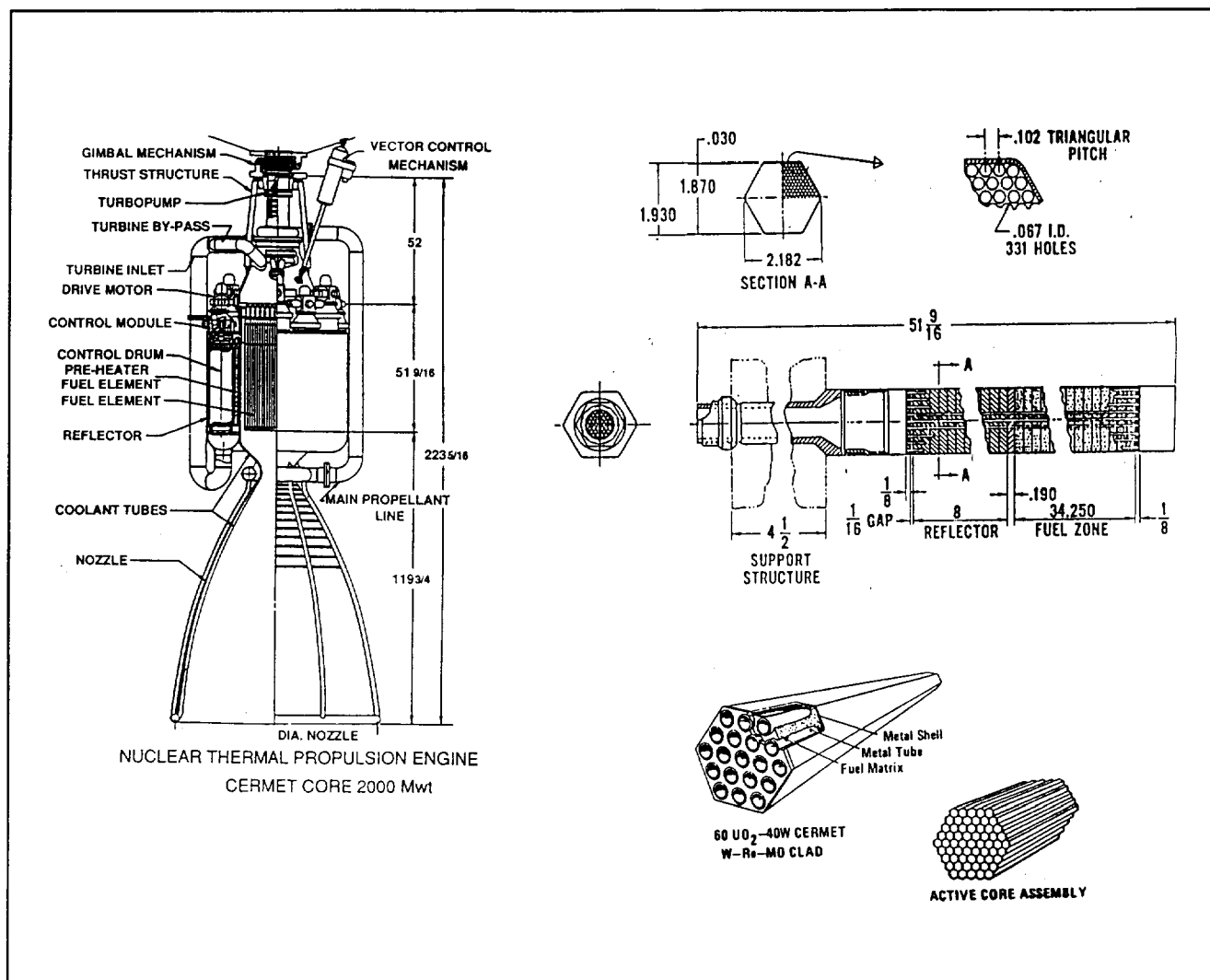


Figure 9 Prismatic CERMET Reactor Concept

element is clad with a tungsten-rhenium cladding on the outside and in each of the cooling holes to protect the fuel from hydrogen attack. A substantial fuel development program was conducted before termination of the program. Tests were conducted up to 2800 K.

A proposed safety feature of the cermet fuel is the retention of fission products - promising minimal release of fission fragments to the space environment. This could be a major advantage over other concepts, if minimum fission fragment release becomes a requirement. Also, the tungsten-rhenium materials may provide inherent safety in the event of a water immersion accident.

Many cermet fuel issues were addressed during the development conducted in the 1960s. These included: UO_2 stability, gas retention in the cermet and tungsten-rhenium manufacturing techniques. Other mixtures may be considered to go to even higher fuel temperatures, such

as uranium-thorium. The key technical issue is to recreate the cermet technology of the 1960s and to demonstrate fuel performance with full size fuel elements. Stabilization of the refractory against grain growth is required for the temperatures proposed. With grain growth comes fuel and fission product losses through the refractory cladding along grain boundaries. A percent or two of the fuel and several percent of the fission products could be lost, depending upon the extremes of temperature, time of exposure and number of cycles.

The specific impulse of the cermet concept presented was 832 seconds, while studies indicate a possible range from 800-900 seconds, depending on maximum temperature capabilities. The engine thrust/weight ratio was

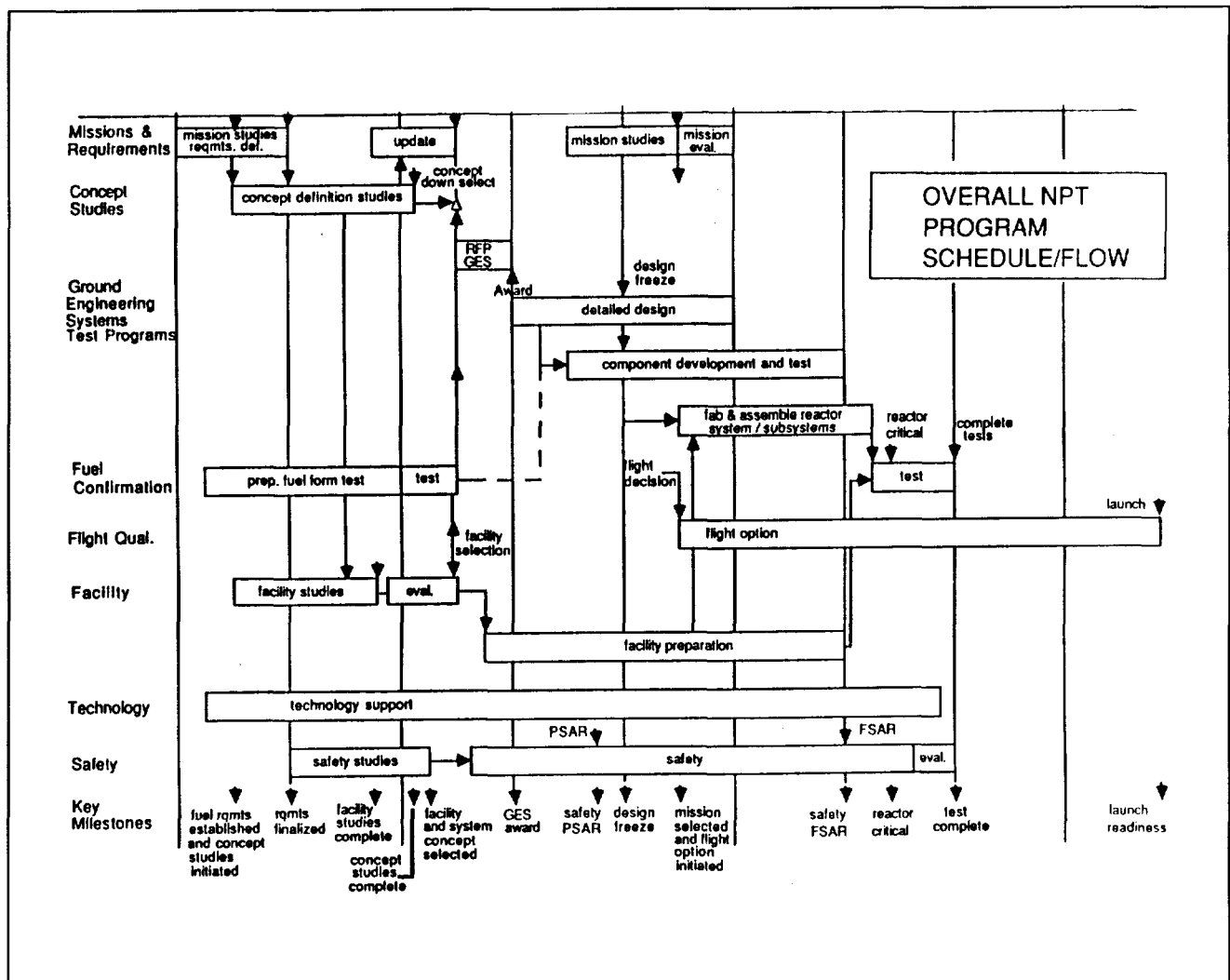


Figure 10 Cermet Reactor Schedule and Task Summary

given as 5.0.

The CERMET reactor development schedule may also be about the same as

other solid core concepts, except in the fuel and materials development tasks and incorporation of the cermet core into a baseline design (see Fig. 10). The core mechanical support structure must be designed in detail including support for the fuel elements from cold end supports. A complete system hydraulic design and test verification, including pre-heat zone, is required. The reactor and reflector control drive assemblies, although similar in concept to NERVA, must be designed and developed.

A full system ground test to qualify the system for a flight test will be required for this and other concepts. Stringent safety and environmental release requirements for the ground test facility are anticipated. Cermet fuels that incorporate positive containment with essentially zero release, may be easier to test than other concepts.

3.1.5 WIRE CORE

The WIRE CORE reactor concept is another 1960s technology fast reactor concept; it was presented at the workshop by Harty of Rockwell International, Rocketdyne Division (Ref. 15). The concept was originally developed by GE for the aircraft nuclear propulsion program. Atomics International did a detailed conceptual design study of the concept in 1963-1965, and fabricated some of the wire fuel (Ref. 44).

The WIRE CORE reactor, shown in figure 11, is an annular flow core. Fuel wires and spacer wires are woven to provide radial outward hydrogen flow in the core, which maximizes the fuel surface area at the high temperatures. About five times the heat transfer surface area is possible compared to the NERVA axial flow concept. Heat transfer coefficients are also significantly higher than NERVA, because the flow over the wires is essentially "tubes in cross-flow," resulting in a smaller reactor, and possible higher hydrogen temperatures (depending on the temperature capability of the fuel wires). Axial fuel element support struts are virtually eliminated with the radial flow configuration.

The fuel wires are made as follows:

- four mil (0.004 inch) UN spherical fuel particles are coated with tungsten;
- the cermet fuel particles are then enclosed in a braided tungsten tube;
- the tubes are then swaged and drawn to 35 mil (0.035 inch) diameter.

This results in a very short heat flow path in the wire, and the high temperature and strength limit is in the tungsten wire, rather than the fuel itself. Core exit temperatures of about 3030 K are projected, with an I_{sp} of about 930 seconds. Axial power shaping is also possible by varying the spacing between the fuel wires and varying the fuel-to-

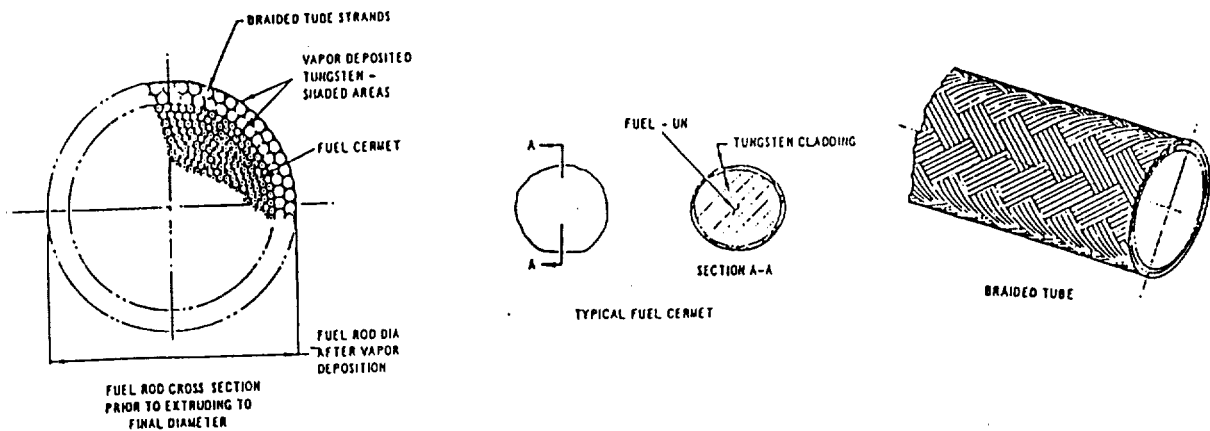
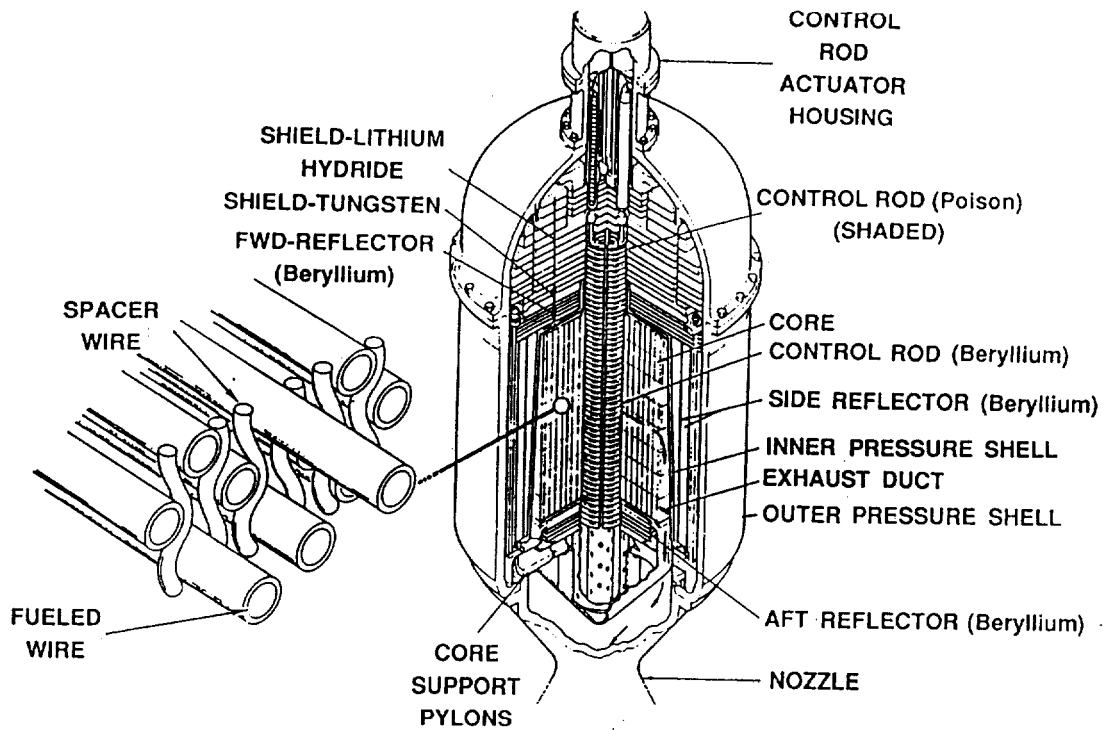


Figure 11 Wire Core Reactor Concept

cladding solidity fraction.

Fuel element development and fabrication are the key initial technical issues for this concept. Reactor design and safety studies will also be required early in the project to guide technology development. Flow stability in the unducted reactor flow path is also an issue and must be investigated.

3.1.6 DUMBO

The Advanced DUMBO reactor concept is a version of a 1950s technology concept, presented at the workshop by Kirk of Los Alamos (Ref. 15). The concept is sometimes called the FOLDED FLOW concept, as the hydrogen

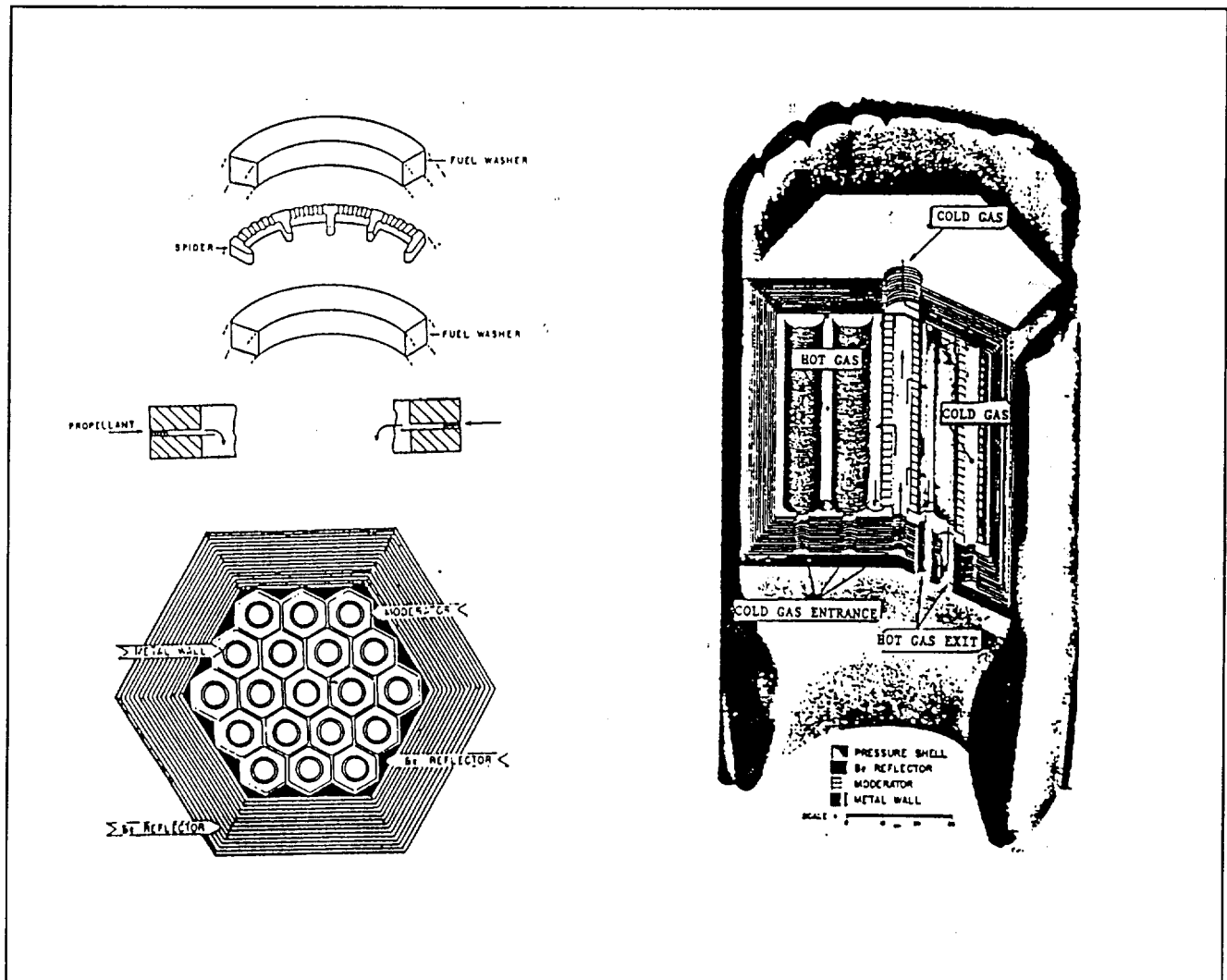


Figure 12 Advanced DUMBO Concept

enters through the top of the reflector, cools the top, side and bottom reflectors and then enters the reactor core at the nozzle end. The

hydrogen then flows upward and radially through a series of uranium carbide fuel washers and "spiders", where the temperature increases (see Fig. 12). The hydrogen then exits through the bottom reflector to the nozzle. Heat transfer surface area per unit volume of fuel would be somewhat larger than NERVA. This concept may be attractive for carbide fuels.

The proposed carbide fuel washers (UC-ZrC) provide a defined hydrogen flow path and are expected to yield more uniform fuel and hydrogen temperatures (than other concepts where the flow path is not defined). Also, corrosion of the fuel may be reduced compared to PBR because of the lower surface to volume ratio. Power density would probably be higher than NERVA, but less than the PBR. Fuel temperatures should be similar to the ENABLER concept for the same fuels; specific impulse should be modestly improved as a result of the improved heat transfer characteristics. Power-flow matching is a concern for the DUMBO concept (as well as the PBR, PELLET Bed, and WIRE CORE concepts), particularly in regions of steep radial neutron flux gradients, and during transients and off-design conditions. Carbide fuel cracking may also be a problem.

Fuel element development and fabrication are the key initial efforts for this concept. Reactor conceptual design and safety studies will also be required.

3.1.7 PELLET BED

The PELLET BED reactor concept was presented at the workshop by El-Genk, of the Institute for Space Nuclear Power Studies at the University of New Mexico (Ref. 15). Preliminary mission analyses were discussed by Haloulakis from McDonnell Douglas. The engine system is similar to the NERVA configuration except in the reactor core (see Fig. 13). Axial flow fuel elements are replaced by a cylindrical chamber that contains spherical fuel pellets approximately one centimeter in diameter. Hydrogen flow is radially inward from a cold "frit", through the pellet bed, through the hot frit to a central cavity, and then axial flow to the nozzle chamber (Ref. 45).

Each fuel pellet is made up of many microspheres of UC-TaC or UC-NbC fuel, encapsulated in carbon and TaC or NbC coatings. These microspheres are then suspended in a graphite matrix to provide a thermal reactor core. The pellets are also coated with a zirconium carbide coating for additional corrosion protection. Power density is estimated to be about 50 percent greater than the NERVA concept. Maximum fuel temperatures of about 3100 K are projected, resulting in an I_{sp} of about 998 seconds, with 71,000 lb_f thrust.

The feasibility of the proposed pellet fuel materials and claddings must be demonstrated. A reactor conceptual design must be performed to provide a consistent comparison with other concepts, and fuel and component fabrication and testing must be accomplished to demonstrate the concept. The hot frit design is expected to be critical to the maximum temperature attainable.

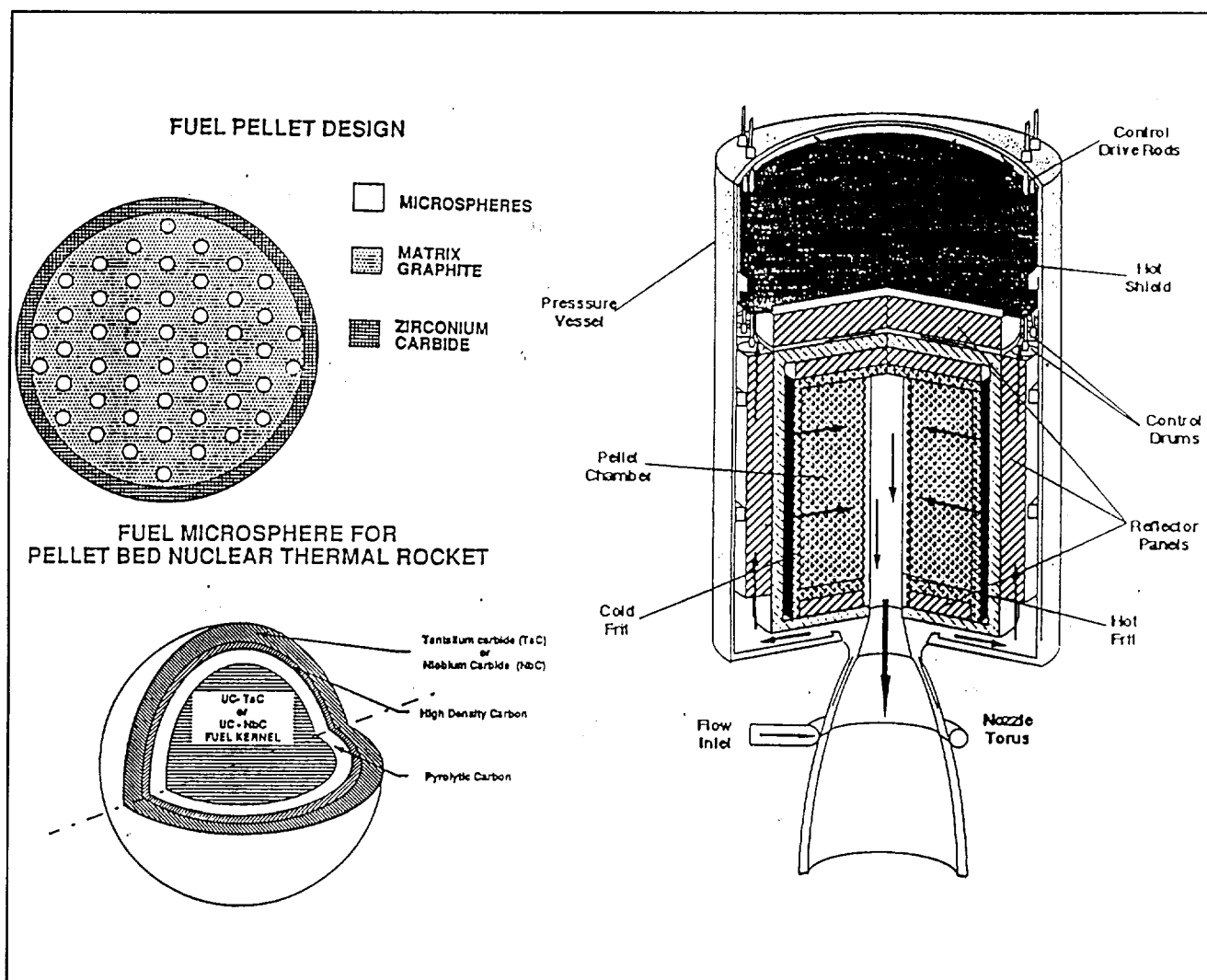


Figure 13 PELLET BED Reactor Concept

The concept advocate claimed several safety features, including sub-critical water immersion and compaction advantages. The fuel pellet design may also provide improved containment of fission products within the pellets, as well as low thermal gradients, and possibly, on-orbit refueling. High height-to-diameter ratio could minimize shielding mass. The concept is also claimed to offer some advantage in passive heat removal. All of these features must be evaluated via conceptual design. A concern with this concept, as well as the PBR and the WIRE CORE, involves the tendency of the coolant to seek the easiest (coolest) flow path, rather than the more difficult (hotter) flow path, contributing to temperature maldistributions and possible fuel melting. Flow control must be demonstrated to validate this concept.

3.1.8 LOW PRESSURE (LPNTR)

The Low Pressure Radial Flow Nuclear Thermal Rocket Concept, or LOW

PRESSURE concept, was presented at the workshop by Ramsthaler of the Idaho National Engineering Laboratory (Ref. 15). This concept, shown in figure 14, features a spherical core with radial flow of the hydrogen from a central cavity through fuel element assemblies. The concept can be adapted to several fuel configurations; a particle bed and a platelet concept were presented at the workshop. The concept includes several unique characteristics. Since the concept operates at low pressure the system is proposed to operate on tank pressure, thus eliminating turbopumps. Reactivity in the core is controlled by the hydrogen in the core, thereby eliminating control drums (Ref. 46).

Operating at a pressure of about 15 psia is projected to result in heat transfer augmentation as a result of hydrogen dissociation-recombination effects, yielding up to 30 percent higher specific impulse. The projected specific impulse of 1200 seconds with a carbide fuel is well below the theoretical for dissociated hydrogen, and an optimized thrust chamber and nozzle design may result in a further increase in specific impulse, if this effect can be realized. These potential I_{sp} improvements come at the expense of increased burn time, and the effects of the more active atomic hydrogen species as it affects corrosion, is not known.

The projected specific impulse for this concept should be near the limit for any solid core concept. The relatively small size (11,000 lb thrust) selected for this study (to reduce testing costs and permit redundancy on a variety of missions), makes engine clustering necessary. However, if the projected benefits of hydrogen dissociation and recombination are attainable, the

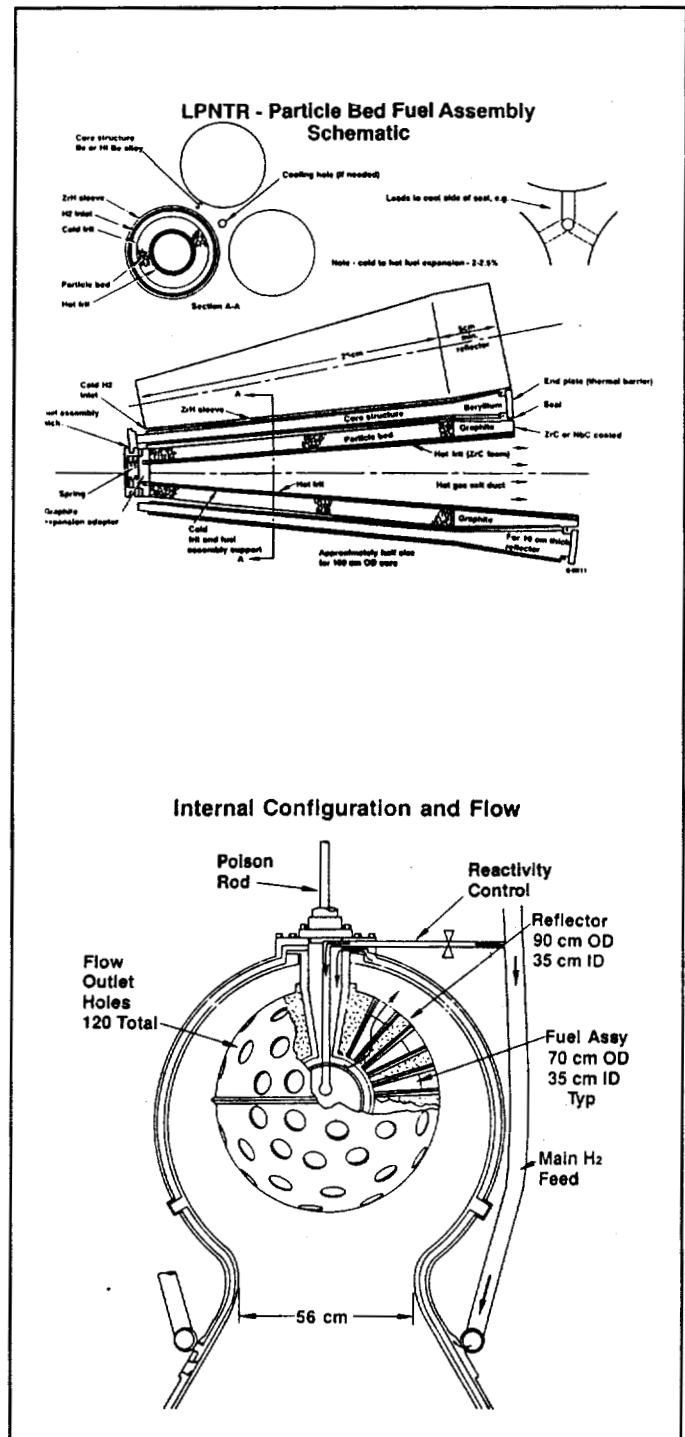


Figure 14 LOW PRESSURE NTR Concept

basic simplicity (i.e., no turbopumps, no control rods) of the concept could be of great benefit in terms of maintenance, reliability and operability. Clustering of seven small engines within a 10 meter diameter system is possible and thrust vectoring could be accomplished by controlling the output of individual engines - thus eliminating thrust vector control gimbals. The low system pressure should also ease the heat transfer design of the nozzle as a result of lower heat flux at the throat.

The major technical issue with this concept centers on the hydrogen dissociation-recombination effects. This effect must be understood before this concept would be pursued. High temperature fuel assemblies are required (as they are for all concepts) to obtain the performance expected. The ability to adequately control the hydrogen flow without turbopumps, and to control the reactivity of the reactor without control rods must also be studied and demonstrated. Because of the low pressure operation, ground testing system requirements will be much different from other high pressure concepts. A ground test facility with full effluent cleanup, must be designed to operate below atmospheric pressure - thus requiring extensive vacuum pumping capability.

3.1.9 FOIL REACTOR

The Fission Fragment Assisted (FOIL) Reactor concept was presented by Wright of Sandia National Laboratory (Ref. 15). This concept is a spinoff from the nuclear pumped laser program at Sandia. The concept, shown in figures 15 and 16, involves applying very thin foils of U- UO_2

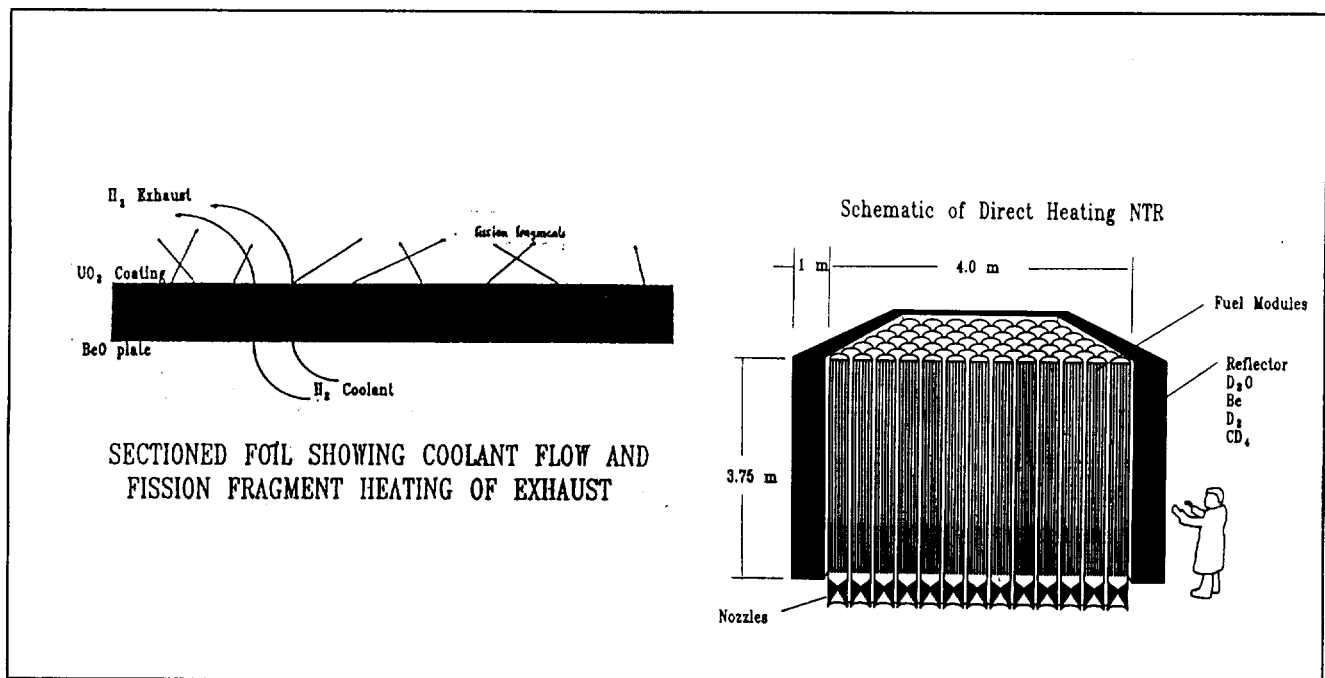


Figure 15 FOIL Reactor Concept

to a substrate, and if the foil is thin enough (1-2 microns), the fission fragments go to directly heat the flowing hydrogen. Thus, it may be possible to obtain hydrogen temperatures greater than the maximum material temperatures in the reactor, with resultant performance benefits.

A reactor module is comprised of annular coolant channels and exhaust channels. Propellant is introduced into the coolant channels from an inlet plenum in a folded flow configuration. The propellant then flows through the porous walls and thin film and into the exhaust channel. Fission fragment heating continues to heat the gas to as much as 1000 K greater than the substrate. The hot gas then flows axially to the nozzle chamber.

Each fuel module is four meters long and 36 centimeters in diameter, having its own nozzle at the end. The pressure vessel is assumed to be carbon-carbon. One hundred modules are needed to go critical because of the very low uranium concentrations in the foils. Power density is only 300 kilowatts per liter, compared to 2 MW per liter for NERVA. Propellant exit temperature is estimated to be 3400K, with a corresponding specific impulse of about 990 seconds.

The proposed system has a very high thrust (600,000 lb_f), but is very large and requires large reflectors to maintain core criticality. The low power density should make energetic accidents unlikely, while the cell modularity may improve reliability.

Critical proof-of-concept experiments will be required to understand the hydrogen gas excitation physics and the dilute system criticality. Thin foils on porous frits and ceramics must be developed. Fuel coatings and reflector cooling technologies must also be developed.

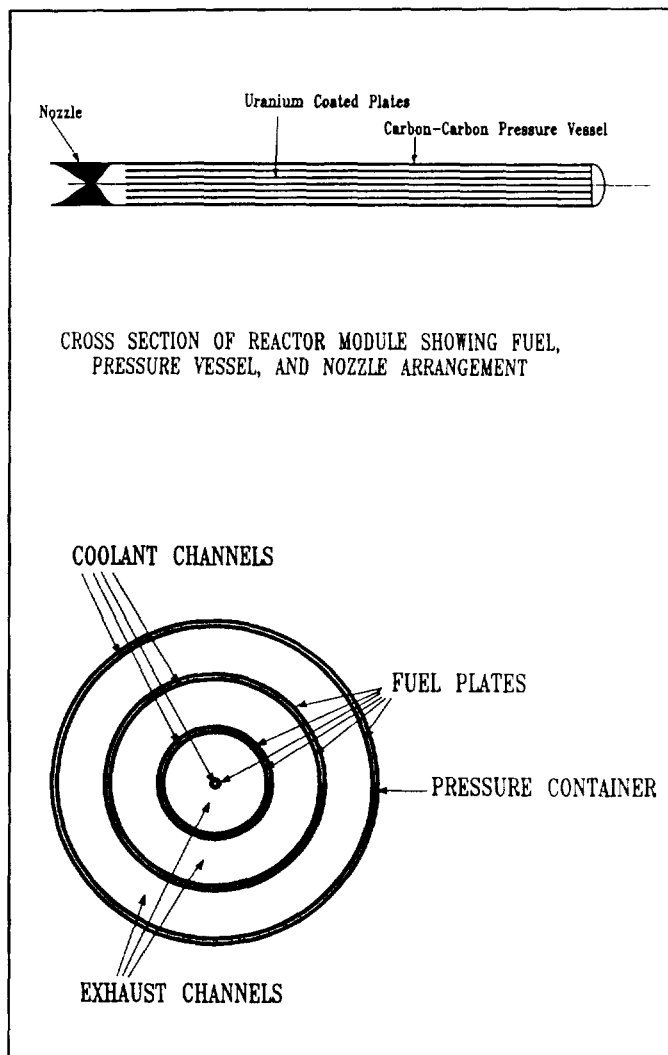


Figure 16 FOIL Reactor Cross Section

3.1.10 TUNGSTEN WATER-MODERATED REACTOR

The Tungsten-Water Moderated Reactor Concept was not presented at the NTP Workshop, but because of the significant weight benefits associated with this heterogeneous thermal reactor, the concept is included for completeness (see Ref. 47). A significant research, design and testing program was conducted on this concept at the NASA Lewis Research Center in the 1960's by Frank Rom and others (Ref. 48). The concept offers high specific impulse, in a light and small reactor.

The reactor, shown in figure 17, consists of an aluminum tank of water with an array of aluminum tubes joining the end header plates. The tubes provide space for fuel elements and flow passages for the hydrogen. First, the hydrogen passes through the regeneratively cooled nozzle, then through a water-to-hydrogen heat exchanger in the reflector area, to remove the heat generated in the water by neutron and gamma radiation, and any other heat that may be absorbed by the water. Next, the hydrogen enters the core aluminum tubes and flows past the fuel elements located in the tubes. Finally the hydrogen exits the core and expands through the nozzle to produce thrust. Insulation is provided by stagnant hydrogen layers in the tube to reduce the heat transferred to the water. The fuel elements are supported by a continuous tungsten tube that runs the full length of the core; tungsten enriched in isotope 184 was used to reduce the fuel loading requirement. A molybdenum radiation shield is also included in the tube.

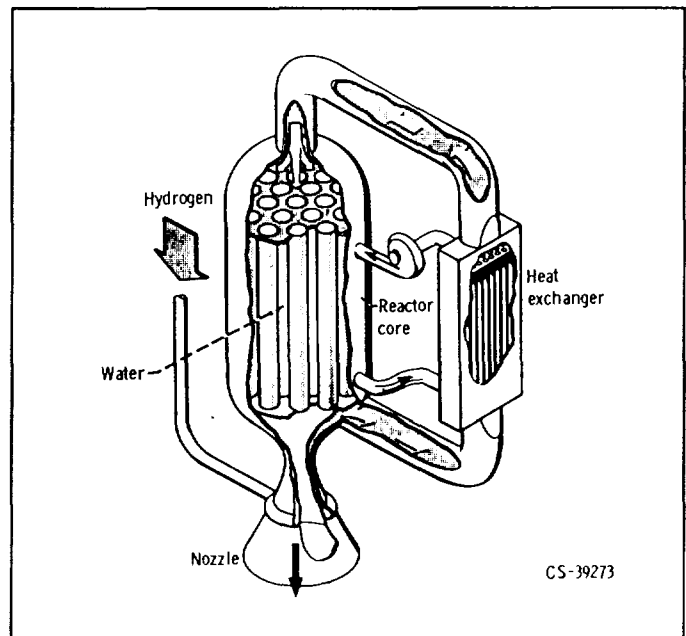


Figure 17 Tungsten-Water-Moderated Reactor Concept

3.2 LIQUID CORE REACTORS

Two liquid core reactor concepts were presented at the NTP workshop, the liquid annulus reactor concept, LARS, and the Droplet Core Nuclear Rocket, DCNR, concept. Also included in this section is a Vapor Transport Fuel Pin concept.

3.2.1 LIQUID ANNULUS

The Liquid Core, or Liquid Annular Reactor System, LARS, was presented at the NTP workshop by Ludewig of the Brookhaven National Laboratory (Ref. 15). In this concept, shown in Figure 18, the fuel is maintained in a molten state and rotated within drums by centripetal

force. Outer layers of fuel remain solid because of cooling, while the inner surface is melted. Hydrogen flow is axial through the concept presented. Because of the very high molten fuel temperatures expected, from 3000 to 5000 K, some of the hydrogen is dissociated, leading to very high specific impulse, estimated to be from 1600 to 2000 seconds. A preliminary conceptual design of the system is presented in reference 49.

Since this concept is currently in a very early concept definition phase, a number of critical technology issues must be addressed. Fluid dynamics, heat and mass transfer at the hydrogen-molten fuel interface are not well understood. A potential problem may exist if the molten or evaporated fuel is carried by the propellant from the system, resulting in unacceptable emissions. Hydrogen dissociation effects must be verified. Also, very little nuclear data or transport properties exist at these temperatures. Stability of the liquid layer during rocket acceleration must also be verified. Reactor startup and shutdown must also be studied and verified.

Critical tests include:

- heat and mass transfer experiments to verify proof-of-concept,
- hydrogen dissociation verification tests to quantify expected benefits, and
- engine test facility planning, including the provision for fission products in the exhaust.

Acceptable emission levels for this concept, (and others), both in flight operation and in test configurations must be addressed early in the project.

3.2.2 DROPLET CORE NUCLEAR ROCKET (DCNR)

The Droplet Core Nuclear Rocket (DCNR) Concept was presented by Anghaie of the Innovative Nuclear Space Power & Propulsion Institute at the University of Florida (Ref. 15). This concept, also presented in reference 50, and shown schematically in figure 19, relies on recirculation of uranium liquid droplets, rather than confinement (as in gas core concepts). The melting temperature of uranium fuels is about 1400

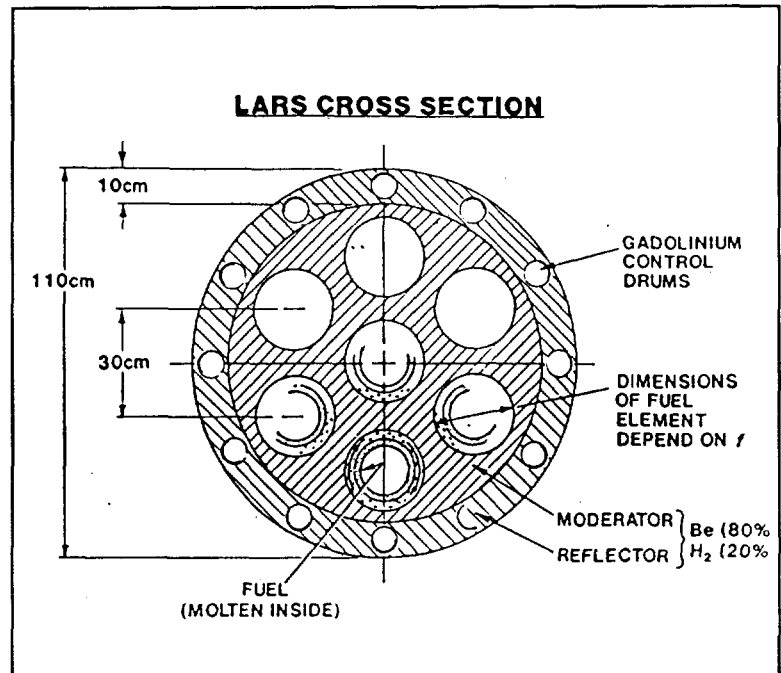


Figure 18 Liquid Annulus Reactor System

K, and boiling temperatures may be up to 9000 K. The liquid phase is believed to be quite stable within this wide temperature range.

Uranium droplets are injected axially with hot (1000 K) hydrogen at the top of the reactor. Tangential injection of hydrogen on the walls of the reactor establishes a vortex film-cooling flow to cool the wall and protect the wall from impingement of the hot liquid droplets, in the upper two-thirds of the reactor. The top of the reactor is fully reflected and moderated. In the lower region of the reactor, the vortex strength is increased causing the liquid uranium droplets to be forced to impinge on a film of liquid lithium-6 on the wall region. The uranium and lithium-6 are then removed to a hydrogen-lithium-6 separator. At the reactor temperatures, hydrogen is expected to dissociate and recombine, resulting in specific impulses in the range of 1500 to 3000 seconds. Fission fragment heating of the hydrogen is also expected, with about 50 percent of the fission fragment energy entering the hot gas.

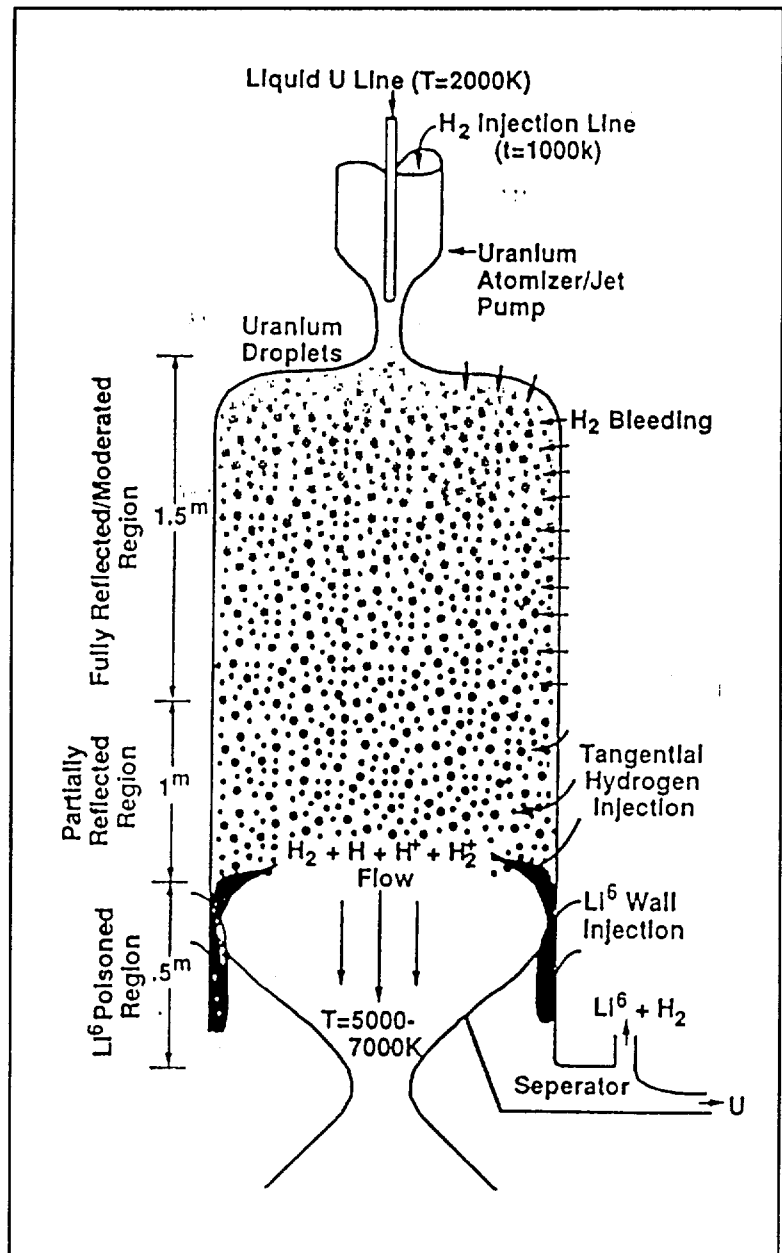


Figure 19 Droplet Core Nuclear Rocket

For the Mars mission considered, the temperature of the hydrogen was assumed to reach 6000 K, 20 percent dissociation and recombination was assumed, for a projected I_{sp} of 2000 seconds - substantially above anything attainable with a solid core. Trip time may be reduced below 200 days and/or propellant usage (IMLEO) may be substantially reduced.

Several critical issues exist for this concept:

- kinetics of the liquid fuel containment and separation,
- very advanced structural components,

- radioactive fission fragments, and possibly liquid droplets, leaving the core,
- High strength, high temperature, refractory structural materials, such as tungsten or tantalum retain high radiation levels,
- rocket nozzle heat transfer design for 6000 to 7000 K operation will be a major issue,
- acceleration effects on droplets,
- and, fission fragment heating effects.

3.2.3 VAPOR TRANSPORT FUEL PIN CONCEPT

Some work was done on this concept in the 1960s at the Lewis Research Center by Frank Rom and others (Ref. 47 and 51). This work was not presented at the NTP workshop, but was discussed at the AIAA/NASA/OAI Conference on Advanced SEI Technologies. The concept was described as a "vapor transport fuel element", and incorporates many common features of a "heat pipe." The isothermal fuel element is shown schematically in figure 20. The pin itself is simply a hollow tube closed at both ends, containing radioactive fuel. Uranium dioxide is indicated in the figure, but other fuels may be even better. Upon startup, the solid fuel melts and then vaporizes and redistributes as indicated. Cold

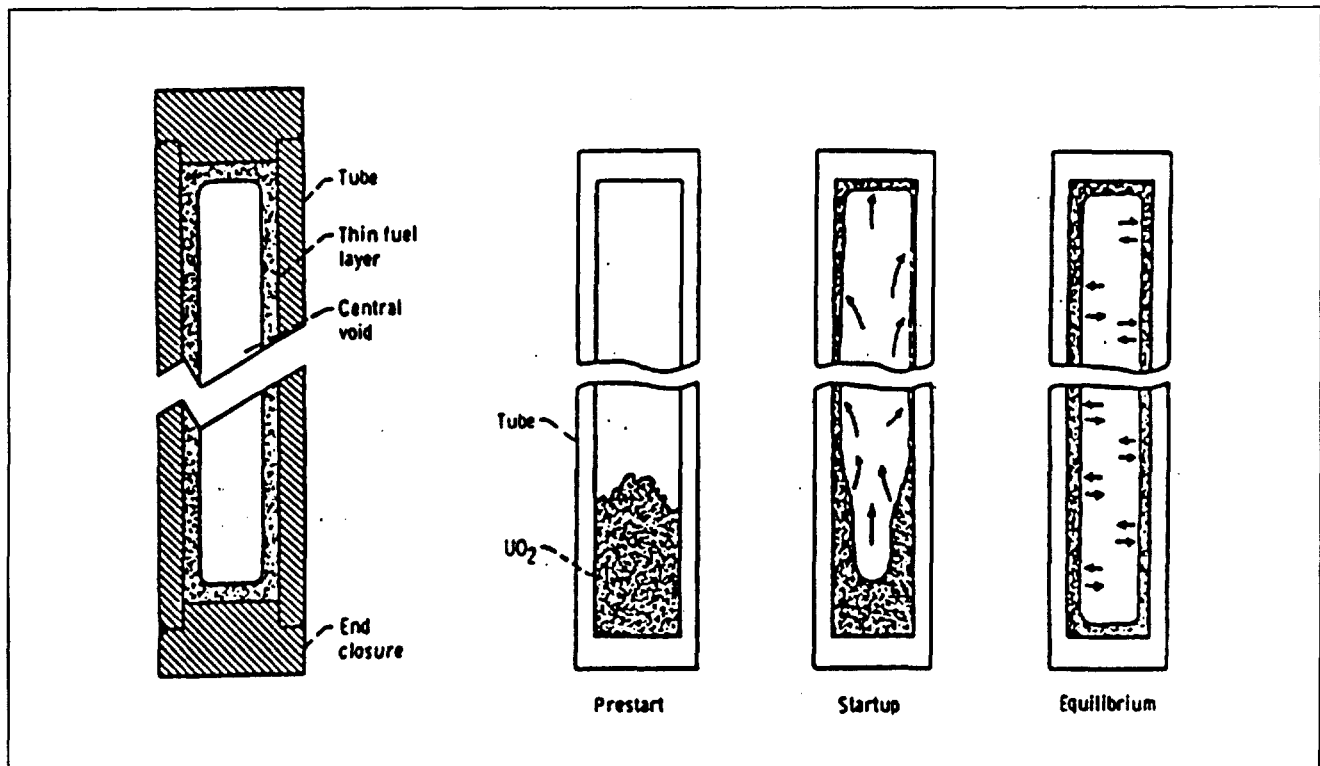


Figure 20 Vapor Transport Fuel Pin Concept

spots are eliminated by selective condensation of fuel on the cold spots. The net result is that the entire inside surface of the fuel pin

would tend to operate at about the same temperature, independent of axial power distributions.

Compared to many other fuel element geometries, this concept was believed to have the greatest potential for fission product retention. Much work is required to optimize this concept in a functional propulsion system, and startup and shutdown controls and reactivity controls will have to be studied. Coupled neutronics, heat and mass transfer studies are required to fully understand the dynamics of the system. Conceptual designs must be conducted while optimizing fuel element characteristics. Finally, fuels and materials must be selected and tested to verify fuel/material interactions at the design temperatures, for the design life, in an appropriate neutron environment.

3.3 GAS CORE REACTORS

Two closed cycle gas core concepts and one open cycle gas core concept were presented at the NTP workshop.

3.3.1 VAPOR CORE

The VAPOR CORE rocket concept was presented by Diaz, of the Innovative Nuclear Space Power & Propulsion Institute at the University of Florida (Ref. 15). This is a uranium tetrafluoride (UF_4) fueled reactor. The vapor fuel is contained in canister assemblies and does not circulate. Hydrogen propellant flows in tubes within the canisters. Containment of the vapor can be accomplished with a number of materials. This concept, also described in reference 52, starts with essentially a NERVA system, with the graphite fuel elements and supporting tie tubes replaced by the vapor fuel canisters arranged in cells, as shown in figure 21. The cell is arranged with a carbon-carbon wall, hydrogen coolant, moderator, uranium tetrafluoride, and helium. The fuel is vapor, resulting in an isothermal heat generation region. A beryllium reflector is added at the top for reactivity, and a graphite reflector is added at the bottom.

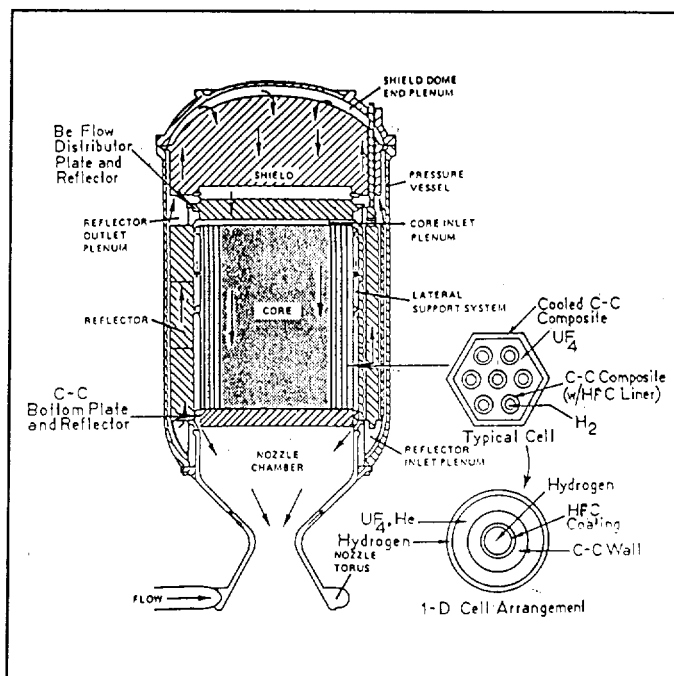


Figure 21 Vapor Cor Rocket Concept

The high fuel vapor temperatures projected (4000 to 5000 K) result in hydrogen temperatures of about 3500 K, and a specific impulse of about

1280 seconds. The core could be launched without nuclear fuel if desired, and the fuel loaded on-orbit. This is believed to be a nearer-term option than other gas core concepts, providing performance better than NERVA, but lower than the open cycle gas core. It is thus believed to be a pathway to the full potential of gas core reactor technology.

Fuel vapor containment and compatibility with wall and structural materials must be verified. A UF_6 test cavity must be built and tested at appropriate power and temperature levels to verify the concept. A nozzle test facility will be required to operate at the projected temperatures and heat flux rates.

3.3.2 NUCLEAR LIGHT BULB

The NUCLEAR LIGHT BULB concept was presented at the NTP workshop by Latham, from the United Technologies Research Center (Ref. 15). The

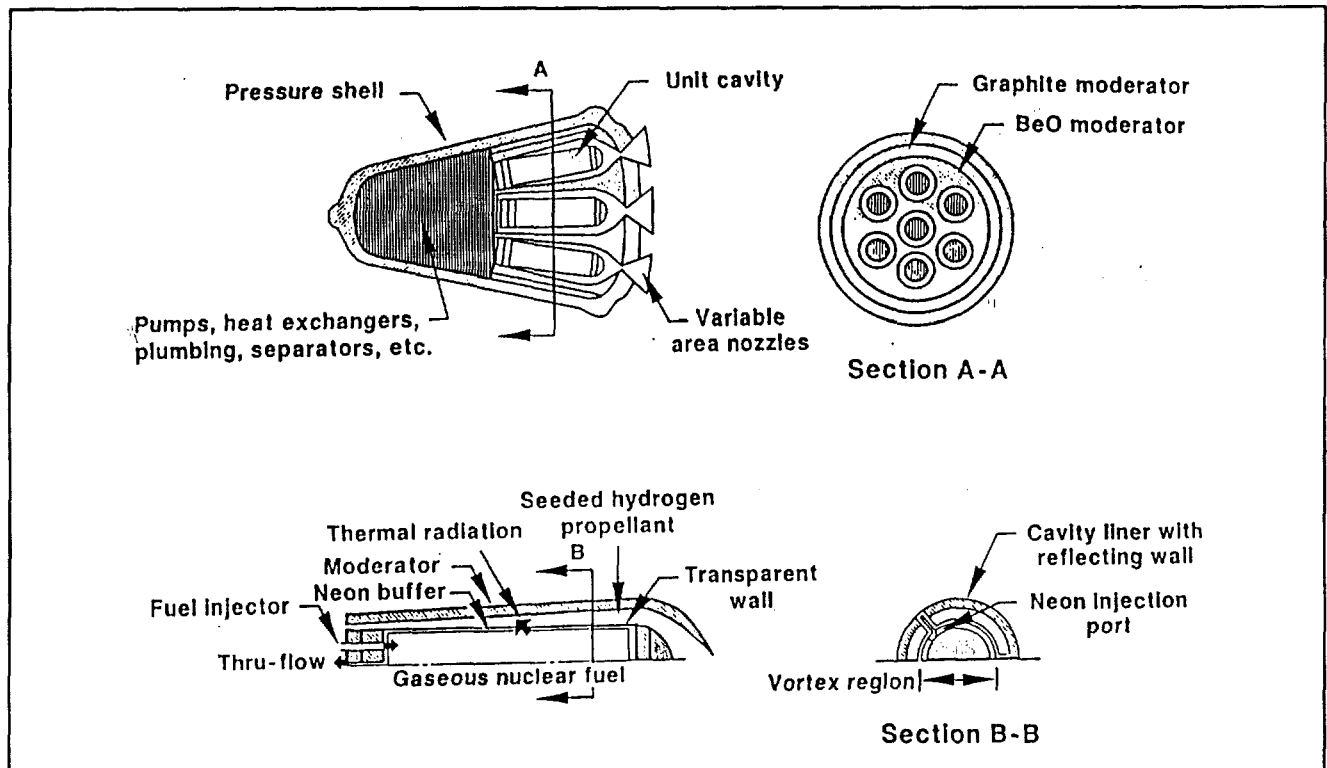


Figure 22 NUCLEAR LIGHT BULB Engine

concept is a closed cycle gas core concept, but has the potential for complete containment of the nuclear fuel. The fuel is mechanically contained in a cylindrical geometry with radiant heat flux passing through internally cooled fused silica transparent walls to a seeded hydrogen propellant, (see Fig. 22). A moderator is added to reduce critical density requirements. U-233 was used in place of U-235, for an advantage in fuel loading. A reference engine was designed in the 1960s and early 1970s, and a seven module engine would fit in a shuttle bay

(see also Ref. 53).

Technical issues include: the seeding problems, the confinement problem, the nozzle heating problem and the fuel handling problems. New materials must be considered in the old designs, and CFD calculations performed to refine the system. System stability must be verified.

A plasma temperature of 7200 K results in an I_{sp} of about 1870 seconds, which can be traded off against trip time or $IMLEO$.

3.3.3 OPEN CYCLE GAS CORE

The OPEN CYCLE GAS CORE Concept was presented by Ragsdale of Sverdrup Technology (Ref. 15). The concept is shown schematically in figure 23. Propulsion is provided by hot hydrogen which is heated directly by radiation from the gaseous nuclear fuel core. A critical mass is sustained in the uranium plasma in the center. It is a thermal reactor in the sense that fissions are caused by absorption of thermal neutrons. The fast neutrons go out to a moderator-reflector material and, by collision, slow down to thermal levels, and then come back to the plasma and cause additional fissions. Hydrogen flows from the propellant tank to a turbopump, regeneratively cools both the nozzle and the reflector, and then flows into the spherical cavity.

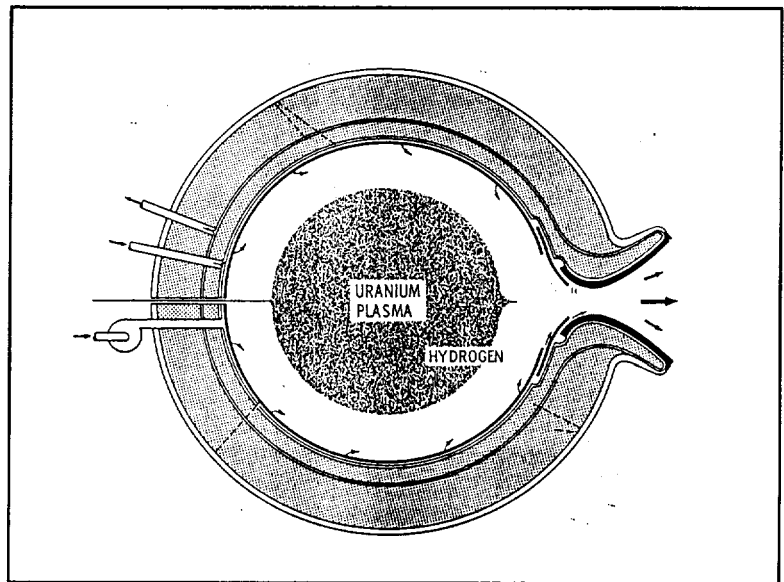


Figure 23 Open Cycle Gas Core Concept

There is direct contact between the uranium plasma and the hydrogen flow. A seed material is added to the hydrogen to help absorb the radiant energy and to protect the walls of the cavity. A recirculating flow field is set up to maintain a stagnation region in the center of the sphere, to prevent excessive loss of fissionable material through the nozzle.

The high plasma temperatures (10,000 to 20,000 K) result in the highest I_{sp} of all the nuclear thermal reactor concepts (>5200 seconds). This can result in very short trip times or huge propellant savings (Ref. 54-55).

It must be demonstrated that the nuclear plasma can be contained with an acceptable fuel loss rate, and an acceptable reactor pressure. With the projected gas temperatures, nozzle cooling will be a challenge. Reference 56 describes critical testing that was conducted at Los Alamos

National Lab in the early 1970s. Also, ground testing of the concept with existing environmental constraints will probably require significant engine exhaust cleanup capability beyond that required for solid core concepts.

3.4 OTHER CONFIGURATIONS

3.4.1 NIMF

The Nuclear rocket using Indigenous Martian Fuel (NIMF) Concept was presented by Zubrin of Martin Marietta Astronautics (Ref. 15). Unlike other concepts, the NIMF concept would use a nuclear thermal rocket for transportation to the Mars surface, and for travel from place to place on the Mars surface. Questions of contamination of the Mars landing sites and landing craft must be answered before this concept will be seriously considered. The unique characteristic of the concept is in the use of carbon dioxide from the Mars atmosphere as the propellant (Fig. 24). A high-powered nuclear thermal rocket engine would be designed to use carbon dioxide collected from the Mars atmosphere as the propellant for traveling to various locations on the surface and for return to the orbiter (or return directly to Earth), thus gaining a very large enhancement of the mission capability with global mobility on Mars.

The spaceship would travel to Mars with just enough propellant to land on the Mars surface, perhaps with a parachute assisted landing. A pump would then be started that gathers atmospheric carbon dioxide, compresses it to about 100 psia, which liquifies the CO_2 , and stores the liquid in the fuel tanks. When the crew wishes to fly away, they simply turn on the reactor, using the CO_2 for propellant, and away they go. They can "hop" to any point on the planet for additional exploration, and simply refuel again using the compression system.

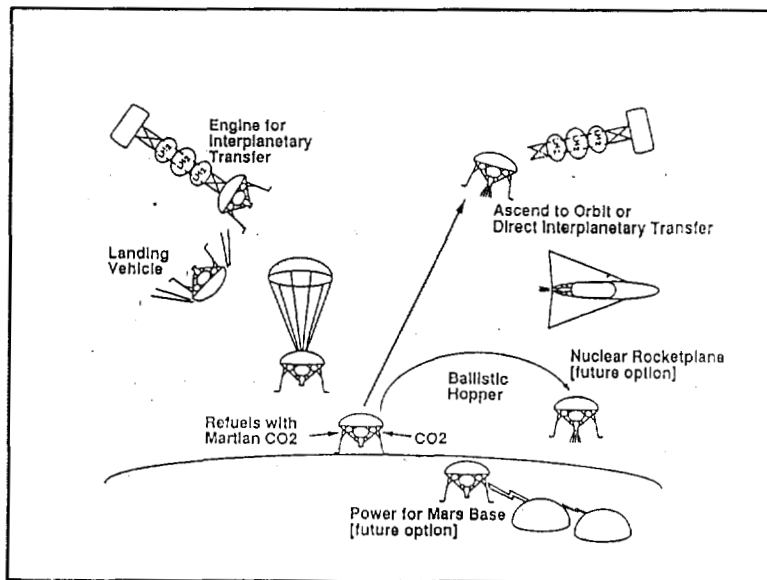


Figure 24 NIMF Concept

NIMF could reduce IMLEO by a factor of two, thus significantly reducing the heavy lift requirements compared to other proposed concepts. The number of sites visited on a mission could be increased by a factor of ten (or more), greatly increasing the science return of mission. These apparent advantages must be compared to the increased risk to the human explorers, since the "hot" reactor lands on the Mars surface, and the astronauts must live and work in close proximity.

Similarly, radioactive contamination of the Mars surface by the rocket effluent must be carefully considered.

High thrust-to-weight NTR engines are required for the "hopper" and to return from the Martian surface to the Earth using indigenous CO₂ propellant (Ref. 57). These engines must also be capable of withstanding the hot corrosive CO₂ propellants, as well as the propellants used on the trip to Mars, such as hydrogen. Fuel materials and coatings development will be required, since the current fuels and coatings will probably not be acceptable.

3.4.2 HYBRID SYSTEMS

HYBRID propulsion systems were discussed by Darooka of General Electric at the NTP workshop (Ref. 15). A hybrid concept in this discussion is taken to mean a combined system that uses a high thrust engine to escape the earth's gravity field (such as a chemical rocket or an NTR), and a low thrust, high specific impulse system, such as a nuclear electric system, for the balance of the mission. A number of system combinations were discussed. A more detailed study of optimum combinations of systems will be required. The additional complexity of the hybrid systems must be compared to possible performance improvement.

3.4.3 DUAL MODE SYSTEMS

DUAL-MODE concepts were discussed at the NTP workshop by Layton (Ref. 15). The remarks were related to work that was done in the early 1970s. DUAL MODE was taken to mean a combined system that uses a high thrust NTR to escape earth gravity and a electrical power generation system, using the reactor cooldown heat or low power, to provide power for electric thrusters and for vehicle electrical power needs (such as propellant refrigeration). As with hybrid systems, more detailed studies will be required to overcome the additional complexity of the dual mode systems.

4.0 NTP TECHNOLOGY PANEL RESULTS

The Nuclear Thermal Propulsion (NTP) Technology Panel was established at the recommendation of the Workshop Steering Committee to refine the planning for the nuclear propulsion technology project, and to compare all of the NTP concepts on a consistent basis. The NTP panel results and recommendations are summarized in reference 30, and will be described in detail in the sections that follow.

4.1 NTP PANEL STRUCTURE

4.1.1 PANEL MEMBERS

The NTP Technology Panel members are shown in Table III. The government members were chosen for their expertise and interest. It is believed that the panel was "balanced," so that most concept advocates

were represented on the panel and member personal biases would be balanced by other member interactions. As noted in Table III, industry and academia responded enthusiastically to the call for industry participation in the panel activities. Their participation was both timely and insightful.

4.1.2 MEETINGS

Five panel meetings have been held in 1991:

January 8	Albuquerque, NM
February 5-6	Washington, DC
March 4-6	Las Vegas, NV
April 8-9	Houston, TX
June 10-11	Idaho Falls, ID

The March meeting in Las Vegas included a site visit to the Nuclear Rocket Development Station (NRDS), at Jackass Flats, NV, the site of the extensive testing of the ROVER/NERVA reactors and engines in the 1960s and early 1970s. Similarly, the June meeting in Idaho Falls included a tour of the extensive experimental reactor test facilities at the Idaho National Engineering Laboratory.

The first meeting of the NTP Panel was held in conjunction with the 8th Space Nuclear Power Symposium in Albuquerque, NM. The panel objectives were presented and discussed. A "strawman" set of mission requirements was presented and discussed. These requirements were needed to establish performance characteristics for nuclear engine systems, and to initially estimate test facility requirements. It was recognized that these requirements would likely evolve as NASA mission studies continue and decisions are made regarding mission architectures. The mission requirements presented were for an "all-up" vehicle; that is, one in which all of the propellant, landing systems, habitats, and return systems were all included in a single vehicle. The all-up vehicle is the system studied by NASA in the 90-Day study (Ref. 9-10). In June of 1991, the Stafford Synthesis Group report (Ref. 17), recommended a "split-sprint" mission to Mars, in which a cargo vehicle would be sent to Mars two years ahead of the crew. The surface habitat and scientific equipment would be robotically delivered to the Mars surface, checked out and ready for the crew when they arrive.

Table III NTP Technology Panel

John S. Clark, Chairman	NASA-LeRC
Marland Stanley, Co-Chair	EG&G/INEL
Patrick McDaniel	AFPL
James R. Powell, Jr.	BNL
Steve Howe	LANL
William L. Kirk	LANL
Bruce Reid	PNL
Frank Thome	SNL
Gary Polansky	SNL
Stan Borowski	NASA-LeRC
Hatice Cullingford	NASA-JSC
Lee Jones	NASA-MSFC
Mitchell Olszewski	ORNL
Roy Cooper	ORNL
John R. Ireland	LANL
Chet Motlock	INEL
Charles W. Terrell	AFPL

Industry Observers

Lew Walton	B&W
Don H. Roy	B&W
Eric Laursen	Lockheed
Nils J. Diaz	U. of FL
Isaac Maya	U. of FL
Samime Anghaie	U. of FL
David Black	Westinghouse
Hal Campen	Aerojet
Bill Campbell	Aerojet
Mel McIlwain	Aerojet
Randy Parsley	P&W
Tom Latham	UTRC
Steve Peery	P&W
Henry T. Smith	Nichols Res.
Stanley Gunn	Rocketdyne
G. H. Farbman	Starpeth
Paul Sager	GDC/SSD
Alex Paulos	TX A&M
Al Saberi	Rockwell
Gordon Kruger	GE
Julie Livingston	Westinghouse
Andrew Klein	Oregon St. U.
Ben Clark	Martin-Marr.
Tal Sulmeister	Martin-Marr.
Kurt Westerman	B&W
Ira Helms	NUS
Bob Fowler	SVR
W. R. Robbins	AEC

The draft Nuclear Propulsion Project Plan (Ref. 11), was reviewed and discussed at the first meeting. The project plan includes an iterative, parallel systems engineering and enabling technology development phase, followed by extensive system testing to verify technology readiness (see Fig. 1). The project will develop the technology to "technology readiness level 6" - TRL-6, that is, through full system ground test completion by 2006. It was noted that flight hardware system development and testing, and space qualification and testing are not included in the project at this time, but also must be conducted before a nuclear rocket system will be ready for operational status. Innovative technologies are also included in the project because of the potential for significantly higher performance and hence, reduced trip times and possibly lower cost.

A summary of the draft nuclear propulsion technology development project plan with major milestones, is shown in figure 25. Continuing project activities are indicated in public acceptance; innovative technology development; and safety, quality assurance, reliability and environmental compliance; as recommended by the workshop steering committee. The width of the lines in the figure represents an estimate of the relative level of effort required in each area. Fuels technology development should be the primary technology focus in the early stages of the project. Other technologies will be included as more funding becomes available.

Major activities early in the project will be required to design and build (or modify existing) facilities to perform the system and subsystem tests. Agency and Department approvals, safety analyses and reporting, and environmental documentation requirements will contribute to the lead times indicated for these major facilities.

Initial trade studies and conceptual design contracts for NTP will help to provide a consistent comparison of concept options, and will help to guide the technology development activities. Hardware design activities will lead to initial concept selection for system testing in the 1998 time period, which should provide systems validated to TRL-6 by the 2006 target date.

Test facility requirements were discussed, as was the input requested by the facilities panel. The importance of the integration of instrumentation and controls technology in the project from the beginning, was stressed. A space flight system verification approach was discussed, and an outline of an NTP test plan was presented (by Allen of Sandia and the Test Facilities Panel). Finally, an approach to accomplish the objectives of the panel activities was discussed and approved.

The second meeting of the NTP technology panel was held in Washington, DC on February 5, 1991. Preliminary output from the Stafford Synthesis Group was presented and the implications regarding the draft NTP project plan were discussed. The proposed reference

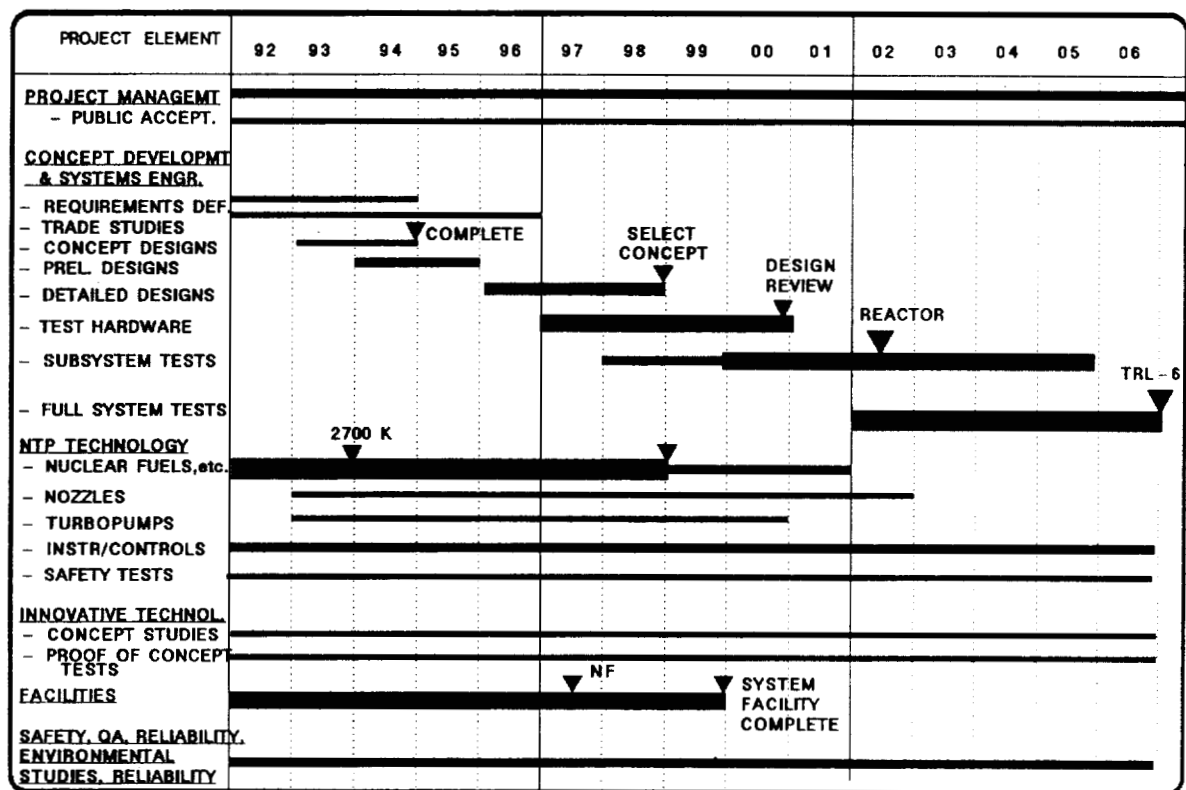


Figure 25 Nuclear Thermal Propulsion Technology Project Plan Overview

mission was discussed; it was shown that for the "all-up" Mars mission, total vehicle thrust levels from 75,000 to 250,000 lb_f are desired. Lower thrust levels would result in longer burn times, which could be a technology (fuel corrosion) issue. Thus, in order to minimize facility impacts, a reference engine thrust level of 75,000 lb_f was selected.

Because of the size of the panel, it was agreed that sub-panels should be formed to address specific issues in smaller working groups.

SOLID CORE TECHNOLOGY SUB-PANEL: The solid core technology sub-panel, chaired by McDaniels, agreed to review and recommend (1) appropriate design reference missions, (2) an appropriate testing and test validation approach, and (3) solid core concept facility requirements. This sub-panel also agreed to review the draft project plan, identify critical tests, test objectives, facility requirements

and appropriate project milestones, and recommend a detailed, overall project test plan.

INNOVATIVE TECHNOLOGY SUB-PANEL: This sub-panel, chaired by Steve Howe, agreed to address the more advanced concepts, those capable of significant performance improvement, compared to the NERVA technology baseline. Critical, proof-of-concept tests were to be identified, and a test plan and analytical approach were to be prepared for the high priority innovative concepts.

CONSISTENT PERFORMANCE SUB-PANEL: This sub-panel, chaired by Stanley, agreed to define the methodology to be used to evaluate the performance of NTP concepts in an internally consistent manner, and to perform the evaluations for a representative subset of the NTP concepts.

The third meeting of the NTP panel was held in Las Vegas, NV on March 4-5, 1991. McDaniel made a presentation on the implications of extensive fission product releases. Robbins presented a proposed flight certification program, that includes rigorous testing and a comprehensive design review process. An "Authority to Proceed" will be required by about 1998 in order to enable a 2008 first flight of an NTR. Major test facility requirements were again discussed and refined. The solid core sub-panel met and defined a detailed technology development plan. The consistent performance sub-panel reviewed decision-making criteria and discussed the system parameters and variables that will be required to adequately characterize the NTP concepts. Missing data and scaling laws were identified.

The fourth meeting of the NTP panel was held in Houston, TX, on April 8-9, 1991. Critical path issues in the project were identified:

- fuels technology and production capability,
- fuel element assembly test facility (nuclear furnace), and
- full system ground test facility.

Preliminary cost estimates for facilities and nuclear testing was presented by Stanley from a task force effort at INEL. Technical issues regarding solid core concepts were reviewed.

A steering committee meeting was held on May 2, 1991 in Cleveland, OH. A number of issues were identified and discussed, as noted earlier. A number of actions were identified for the various panels; the NTP issues will be discussed in detail in later sections of this report.

The fifth meeting of the NTP panel was held at the Idaho National Engineering Laboratory, (INEL), in Idaho Falls, ID on June 10-11, 1991. Discussions at this meeting focussed on the actions assigned by the steering committee, and various interactions between panels. The Discussion of Results section that follows will present the findings and recommendations of these sub-panels, and the full NTP panel.

4.2 DISCUSSION OF RESULTS

4.2.1 PERFORMANCE OBJECTIVES

Table IV summarizes the performance objectives used for the project planning. There was a great deal of discussion regarding some of these numbers, and no consensus was reached on the appropriateness of each of these parameters. It was agreed by all, however, that in order to make a first iteration on the test requirements and facilities definition, an initial set of performance objectives would be necessary, and the objectives shown were used. Again, an "all-up" mission was assumed, and these performance objectives could change somewhat for a "split-sprint" mission.

The most important parameter, from an engine design standpoint, is the exhaust temperature. This temperature was chosen to be about 2700 K, which corresponds to a specific impulse of about 925 seconds. Temperatures in this range were achieved with composite fuels in the NERVA program, so it is believed that this temperature can be achieved with relatively low technical risk. Appropriate safety, reliability and design margins will be required, of course, for astronaut-rated systems. Higher temperatures have been proposed for several of the concepts, and NTP systems should be designed to evolve to these temperatures as they become available. System reusability will ultimately become a goal to minimize operations costs when interplanetary travel becomes "routine." The Stafford Synthesis Committee (Ref. 17), has recommended a single vehicle per mission, with engine disposal at the end of the mission to heliocentric orbit.

Engine thrust level is also an important design parameter and strongly affects the ground test facility and exhaust cleanup system cost. As discussed earlier, the optimum thrust level for an "all-up" mission to Mars is about 75,000 lb_f. It is interesting to note that the NERVA engine thrust level was optimized for a lunar mission, also at 75,000 lb_f. Lower thrust levels may be appropriate for a split-sprint mission, and of course engines may be clustered to provide almost any desired thrust level, with some significant advantages in "engine-out" capability. Studies continue to evaluate these tradeoffs.

A nozzle chamber pressure of 500-1000 psia should be well within current technology for both nozzles and turbopumps. Space Shuttle Main Engine (SSME) technology is well beyond the 1000 psia range.

Table IV NTP Performance Objectives

PARAMETER:	STATE-OF-THE-ART:	OBJECTIVE:
THRUST, LB _f	75K-250K NERVA- PHOEBUS	50K-125K MAY CLUSTER
SPECIFIC IMPULSE, Sec.	825	> 925
CHAMBER PRESSURE, psia	450-3000 NERVA- SSME	500-1000
EXHAUST TEMPERATURE, K	2300-2500 NERVA	> 2700
	NOZZLE, TPA 3100 SSME	
LIFETIME, hrs	SINGLE BURN 1.0 CUMMULATIVE 1.5	1-3 3-10
REUSABILITY (Missions)	1	up to 5

Engine lifetime was chosen to be approximately the same as the NERVA state-of-the-art: one hour maximum single burn and about 1 1/2 hours total burn time per mission. The lifetime objective shown is related to the testing lifetime required to validate technology readiness. It was the consensus of the panel that about three times the expected burn time per engine, and three times the number of start-up and shut-down cycles, would have to be demonstrated in a nuclear ground test facility at full operating conditions to validate technology readiness.

4.2.2 TECHNICAL CHALLENGES

There was unanimous agreement that the highest priority technology development efforts should be (1) high temperature fuels and materials development, (2) long lead time facilities design and construction for technology validation testing, and (3) conceptual design contract studies to focus the technology development efforts. Instrumentation development, neutronics, controls, and diagnostics system integration must also be included in the project plan from the beginning.

4.2.3 SOLID CORE SUB-PANEL RESULTS

The solid core sub-panel recommended that a technology development plan be developed for nuclear thermal propulsion technology that would meet the current estimated schedule for the first manned trip to Mars in 2014, as recommended by Stafford (Ref. 17). This date was originally 2016 when the sub-panel started work. This schedule takes into account the successful technology development effort carried out under the ROVER/NERVA nuclear rocket development program of the 1960s, which provides an excellent starting point for the technology development. A list of some of the top level milestones that must be met to meet the scheduled first manned flight to Mars in 2014 is given below:

YEAR	MILESTONE
1993	Lab-scale demonstration of 2700K reactor fuel
1994	Complete conceptual designs of selected concepts for piloted Mars mission
1997	Nuclear furnace facility complete
1998	Select NTR system for systems testing
1998	Flight system design freeze; Authority-to-Proceed with Phase C/D
1999	Systems facility construction complete; First NTR reactor design review complete
2002	First NTR reactor test complete
2006	Full system ground testing complete for all concepts, verifying Technology Readiness Level 6, (TRL-6) for NTR
2008	First flight of NTR system
2009	First human-piloted lunar flight of NTR system
2011-late	First Mars robotic flight of NTR system
2014	First human-piloted Mars NTR mission

The schedule outlined above may be optimistic given the limitations imposed by current initial budget projections. However, the sequencing is correct, and it provides a basis for planning the required activities. Since a nuclear rocket engine was built and tested during the ROVER/NERVA program, the technology development plan does not appear to require major technology breakthroughs to be successful. There appear to be many areas that can be improved by more advanced materials, better computational tools, and perhaps improved component and system designs. An extensive and comprehensive engineering effort will be required, however, and the approach recommended in planning this effort was to identify a minimum cost, concurrent engineering approach, consistent with adequate safety margins and reliability and risk management considerations to ensure a very high probability of success for the overall effort.

The plan can be broken down into five phases as shown in figure 26. These are:

Phase I: Conceptual Design and Technology Development: This phase should include three major activities, conceptual design, fuel technology development, and facility design and environmental studies. Conceptual design contracts should be placed with industry teams to design the nuclear stage and engine. Fuel development should start by recovering the NERVA composite fuel technology, and initiate fabrication and testing of other fuel concepts that have been proposed. Facility design, site selection, safety and environmental documentation, and procurement efforts should be started by the government to develop the major new test facilities that will be required.

Phase II: Preliminary Design and Concept Specific Technology: During this phase the number of participating industrial teams should probably be limited to two or three, each led by a vehicle stage designer. Fuel element concepts should be tested, either in an existing experimental reactor, or in a new "nuclear furnace-like" facility that may be required to test specific fuel element designs under realistic test conditions. Based on the performance of the fuel elements in the anticipated operating environment, up to three design teams should be selected to develop prototype engines. In order to be ready for a first NTR flight in 2008 as planned, an "Authority to Proceed" will be required at the end of Phase II, about 1998, to initiate the development efforts for flight hardware. These efforts, Phase IV, should proceed in parallel with Phase III, the prototype system testing.

Phase III: Engineering Design and Prototype Testing: Using a concurrent engineering approach, this phase will be aimed at developing the prototypes for flight qualification. The development of competing prototypes is considered to be essential to control costs and maintain development schedules. The development of two prototypes will not double the cost of

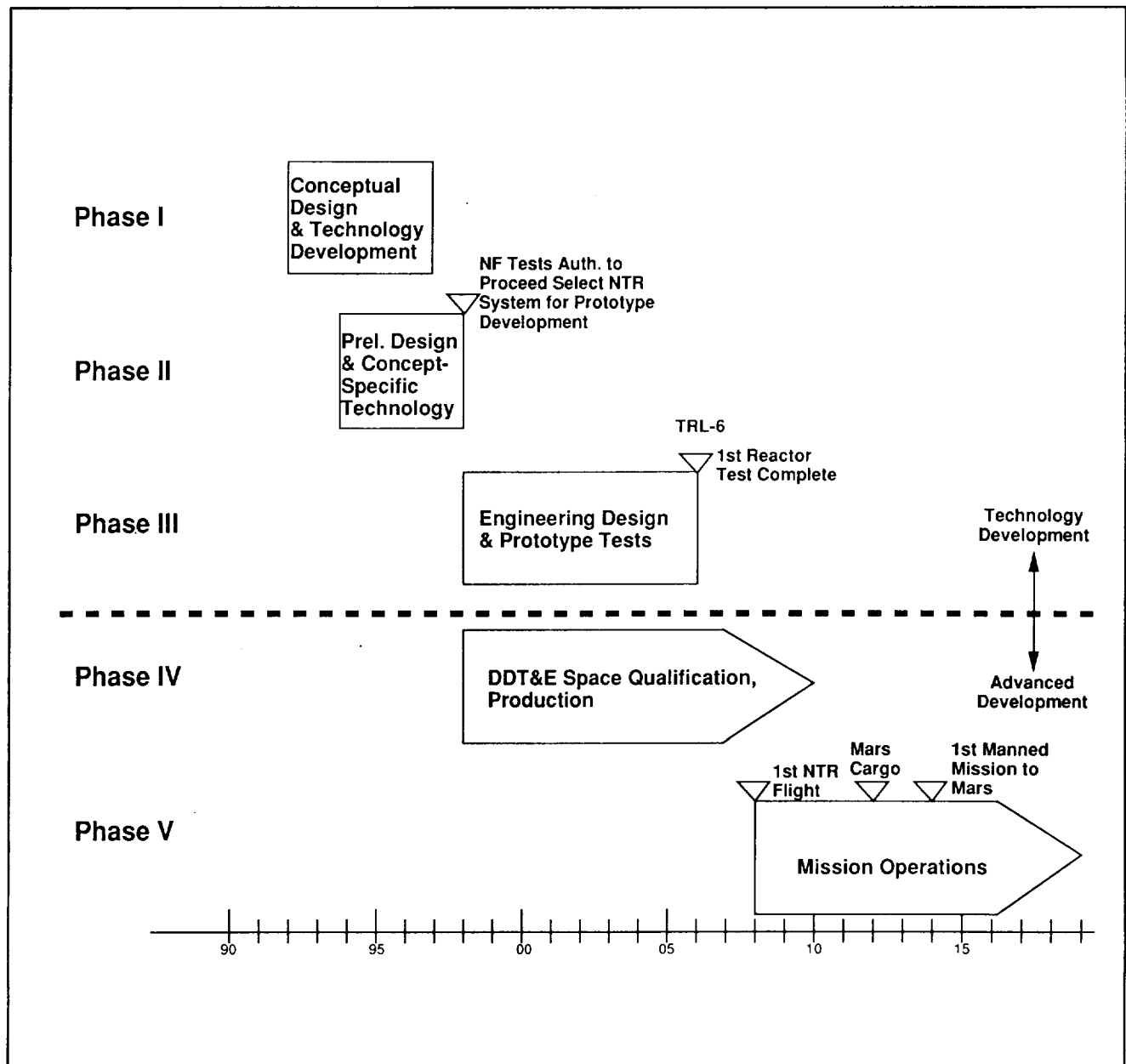


Figure 26 NTP Concurrent Engineering Approach

the development effort because of the single investment in facilities that will be required. Based on the performance of the prototypes, a decision will then be made to commit to full scale development and production of a single engine design.

Phase IV: Full Scale Development: This phase will involve the final engineering and production of the flight engines for Lunar and Mars exploration. In order to be ready for a first NTR flight in 2008, this phase should be initiated in parallel with the technology development phases, utilizing a concurrent

engineering approach. Provisions should be made in this phase of the project to provide a contingency of at least 20 percent, both funding and schedule, between planned engine qualification and first flight. Hardware budgets should be adequate, since the only true reserve in a development program is extra hardware at the time problems occur. Hardware lead times preclude an instant infusion of funds from having a positive near term impact relative to problem resolution. If hardware is available when failures occur (and they will occur), modifications can be incorporated and testing resumed. If the test hardware is not available, a schedule impact of months, and perhaps years, can occur.

Phase V: Mission Operations: Mission Operations will start with the first unmanned NTR flight in 2008, to validate on-orbit assembly procedures, instrumentation and control functions, including autonomous operation, start-up and shut-down, and engine disposal. The initial flight could be followed by routine cargo and manned missions from earth orbit to lunar orbit, and return. A full simulation of a manned Mars mission, in lunar orbit, should be planned to gain operating experience and confidence in the transportation system, as well as experience in long periods of weightlessness and isolation. The first cargo mission to Mars would leave earth in late 2011, followed by the first manned mission in 2014. It is expected that subsequent missions would follow at each 26-month opportunity.

A number of "critical-path" activities have been identified as long lead time efforts and should be started as soon as possible. These efforts are (1) facility design and construction, (2) nuclear fuel development and (3) conceptual design and modelling activities. As part of this planning effort, a preliminary set of requirements were generated for the NTP facilities. The activities required for fuel development were also outlined. However, neither of these activities can proceed very far without a strong design effort to lay out system technology requirements. In a limited funding environment, it is recommended that conceptual design efforts be initiated as soon as possible to guide all of the other efforts, until more funding becomes available. Development plan activities are outlined below.

4.2.3.1 NTP Technology State-of-the-Art

As background for the detailed test plan description, this section is included to review the state-of-the-art of the various technologies associated with nuclear thermal propulsion systems.

The performance requirements for the projected NASA space exploration missions are more demanding than for any nuclear reactor design ever attempted. The following is a list of some of the requirements which affect the nuclear thermal rocket reactor designs of all types to varying degrees:

- fuel must have required life (greater than 1 1/2 hours) at very high temperatures (greater than 2700 K) in flowing hot hydrogen,
- fuel must have a well-defined, stable composition and physical properties in all of the demanding temperature, radiation, corrosion, and space environments,
- fuel must be capable of multiple cycle operations (up to eight cycles per mission,
- design must provide adequate safety and reliability margins during both design and off-design operation,
- system must have low mass and volume to reduce launch costs,
- fission product releases must be as low as reasonably achievable,
- production, fabrication and assembly must be cost effective.

The following sections describe the state-of-the-art of various reactor concepts and some of the technical issues that must be overcome to meet these requirements in the various approaches being considered.

4.2.3.1.1 Fuels/Coatings

Fuels and coatings technology development will be critical to the goals of the project.

4.2.3.1.1.1 NERVA Derivative Reactors (NDR)

Three fuel types were studied in the NERVA/ROVER Program; the NDR concept was described earlier in Section 3.1.1 and 3.1.2, and is shown in figures 4 to 6:

- (1) Beaded Graphite (fuel beads dispersed in a graphite matrix),
- (2) Composite (20 to 30 percent UC-ZrC, dispersed in a graphite matrix), and
- (3) Solid Solution Carbide

Beaded Graphite: Extruded beaded graphite fuel elements were the primary focus of the KIWI/NERVA programs through the KIWI and the NRX-A6 and XE engine tests. The fuel elements were 3/4 inch hexagonal elements 52 inches long, with 19, approximately 0.10 inch diameter holes. These were used in clusters of seven elements, where the central element was unfueled and contained an insulated structural support tie tube. A hot-end interlocked support block supported the pressure drop load through the tie tubes to the cold end support block. The holes and hot end of the fuel element were CVD (chemical vapor deposition) coated with either

NbC or ZrC coatings about 2 mils thick to protect these surfaces from the hydrogen coolant. The fuel beads were dispersed throughout the graphite to provide a homogeneous thermal reactor.

The following data shows the progressive improvement in coating effectiveness during the NERVA program. The NRX-A6 test showed a performance and life capability of over one hour at 2430 K (4380 R) fuel element exit gas temperature (Ref. 58).

<u>Reactor</u>	<u>Weight Loss, Grams/minute</u>
NRX-A3	1.0
NRX-A4	1.1
NRX-A5	0.9
NRX-A6	0.2

Upon post test disassembly of the NRX-A6 core, 85 percent of the fuel elements remained intact while 13 percent had one or more breaks. It should be pointed out that NRX-A6 fuel elements were broken due to mechanical effects of binding, while NRX-A3 to -A5 elements were broken because of corrosion weakening. Figure 27 illustrates the distribution by gross weight loss of the NRX-A6 fuel elements for the entire test. The core average weight loss per element is 13.1 grams with a standard deviation of 5 grams.

A radial distribution of average gross weight loss averages is presented in figure 28 for the NRX-A6 (Ref. 59). The insensitivity of the distribution with radial position results from the flatness of the radial power shape achieved in the NRX-A6 core.

There were two kinds of corrosion: (1) hot end diffusion of carbon from the graphite substrate through the coating because of depletion of carbon at the surface of the coating, and (2) cold end corrosion caused by direct contact of hydrogen with the

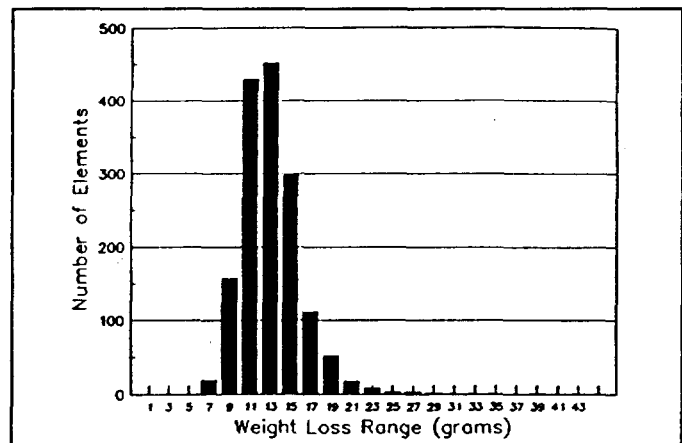


Figure 27 Distribution of NRX-A6 Fuel Element Post-Mortem Gross Weight Loss

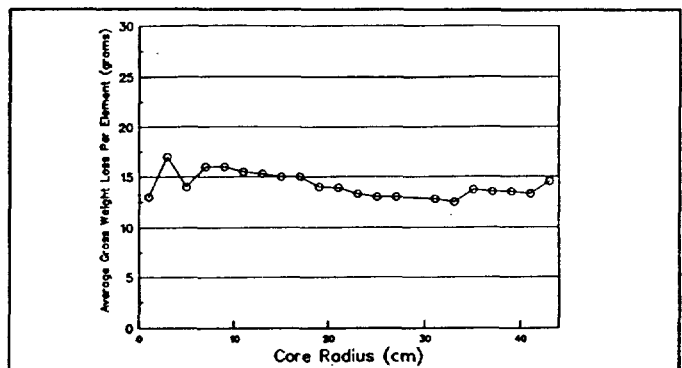


Figure 28 Radial Distribution of Average Post-Mortem Gross Weight Loss

substrate in the base of micro-cracks in the coating. These cracks were caused by the difference in thermal expansion between the graphite and the carbide coatings. The latter corrosion was sometimes referred to as "mid-range corrosion." Actually, the corrosion peaked at about 18 inches from the front end - not 26 inches. Figure 29 shows some typical patterns of carbon loss along the NRX-A6 fuel elements. The figure shows the loss predicted by diffusion, plus the predicted cold end corrosion, which includes the effects of the cracks, and the actual average corrosion experienced.

In the NRX-A6 tests, the NbC coatings were "overcoated" with a thin molybdenum coating designed to fill the microcracks. This was effective and reduced the cold end loss substantially in the cyclic NRX-A6 tests. The carbon corrosion losses occurred primarily at the coating-to-substrate interface and weakened the coating bond, which strongly affected the useful life of the fuel elements by causing progressive corrosion. The basic parameter for interpreting the test results was taken to be the carbon loss per inch of fuel element, with about 0.30 grams per inch loss being thought to be a tolerable level so far as remaining strength and general fuel appearance and properties were concerned. More corrosion was encountered in some local sites without any obvious deleterious effects. Actually, the corrosion situation is much more difficult to analyze because there are several chemical regimes (methane, pyrolytic deposits, acetylene) that occur along the fuel elements as the hydrogen combines with the carbon, and the hydrocarbons present in the hydrogen stream have an effect on the results. Since the presence of parts-per-million levels of hydrocarbons in the hydrogen gas stream favorably affect the progression of surface corrosion, this needs to be explored further. Also, it was found to be advantageous to coat the cold end of the fuel element at lower temperatures (since they operate at lower temperatures), to better match the coefficient of thermal expansions. Together with the molybdenum "overcoat", this significantly reduced the so-called mid-range crack root corrosion.

A substantial effort was made to develop higher coefficient of thermal expansion (CTE) graphites. Niobium carbide, NbC, was the principal coating material used in the NERVA program, but the improved corrosion resistance of zirconium carbide, ZrC, was noted late in the program (Ref. 40-41). ZrC has a relatively high vapor pressure at the

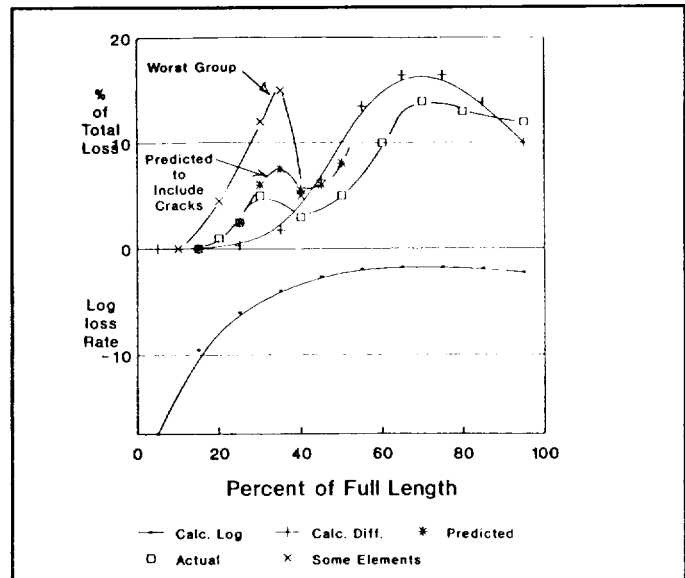


Figure 29 Carbon Corrosion Loss Profile, NERVA Fuels

operating temperatures, however, and that must be accounted for in future work.

Composites: The tendency for progressive corrosion with time, problems with coating adherence, and some of the localized corrosion pockets encountered in the beaded graphite fuel elements led to the development of the composite fuel type. This fuel used a dispersion of 20 to 30 percent fueled mixed carbide in a graphite matrix. This had two benefits:

- (1) the adherence of the coating was greatly increased because of the direct bond of the coating to the carbide portion, and
- (2) even if corrosion depleted the graphite locally, the interlaced (bonded) carbide phase remained in place and the element survived better because there were fewer instances of severe local corrosion.

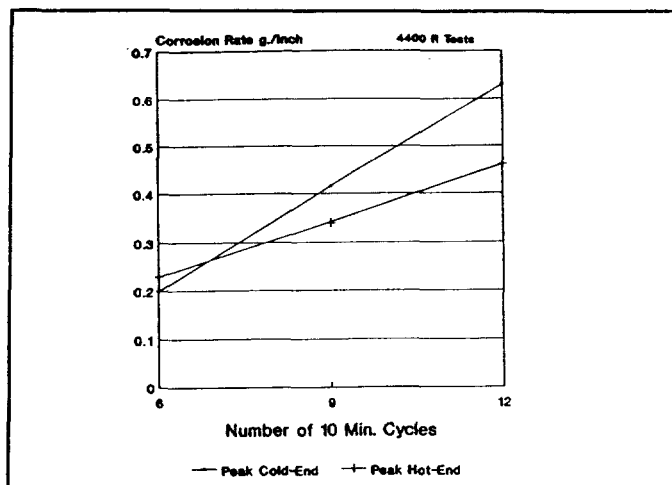


Figure 30 Cyclic Corrosion of Graphite Composite Fuel Elements

The two types of corrosion described above did not respond the same in cyclic tests. The diffusion-controlled loss increases at a lower rate than the crack-induced loss in cyclic tests. Figure 30 shows this effect for some of the composite elements (Ref. 40-41).

The Nuclear Furnace 1 (NF-1) reactor was designed to test new types of experimental fuel elements and improved coatings (Ref. 41). Six tests were conducted during the summer of 1972 while the reactor was loaded with a total of 49 fuel element cells. Two of the cells contained carbide fuel elements while the remaining 47 contained two types of graphite-carbide composite fuel elements. Due to the numerous fractures of the carbide elements, only the composite element were evaluated for mass loss. Over the final three tests, NF-1 was operated at maximum power for a total of 98.9 minutes with a fuel exit temperature of about 2472 K (4450°R). During this test time, the average mass flow rate per channel was 0.0026 pounds per second and the core exit pressure was 464 psia.

Upon post test disassembly of the NF-1 core, the composite fuel elements with the least corrosion were the LASL "replacement" elements with 35 percent carbide. For example, the mass loss rate for an element from LASL Extrusion Lot 56 was 7.8 grams over the entire test series. While this value equates to a weight loss per element of 0.08 grams per minute, which is lower than the 0.19 grams per minute for the NRX-A6

graphite element, upon closer examination the performance was not so favorable. Figure 31 presents the axial variation in the surface corrosion for a composite element from Lot 56. Again, the rise in the central region represents the mid-band corrosion problem. The mass loss in the mid-band region is caused by hydrogen reaction with the fuel matrix through cracks in the channel coatings. The cracks occur due to a mismatch in the thermal expansion coefficients between the fuel matrix and the coating; the mismatch occurs because the coefficients are optimized to match near the fuel element end where temperatures are highest. The replacement elements were developed with essentially crack-free coatings and were expected to have little, if any, mid-band losses. However, figure 31 shows that significant mid-band corrosion did occur. In fact, when compared to the axial variation for the NRX-A6 graphite elements in figure 32, the mid-band corrosion was significantly higher.

The results of these tests showed that corrosion, although not desirable, should not represent a structural problem for one hour operation with either the graphite or composite elements. Modifications in the manufacturing process for the composite elements may reduce the mid-band corrosion even further, thus improving the over-all performance.

Later, in conjunction with the nuclear furnace fuel development efforts, NF-1 and NF-2, the NF-1 GEM-1 and the NF-2 grade GEM-2 coating processes evolved (see Ref. 41). The approximate performance regimes of these several fuel types is shown in figure 33. This information is better shown in the Arrhenius format because the chemistry involved follows activation energy laws. Figure 34 was prepared for that purpose.

A secondary benefit of using the composites was that the CTE of the fuel element was higher, hence there was a better match with coating expansion and contraction (Ref. 60). The strength properties of the composite elements were comparable with the beaded graphite elements. The composite element was tested in NF-1. Improvements in that type fuel element were developed for testing in NF-2, but the tests were not

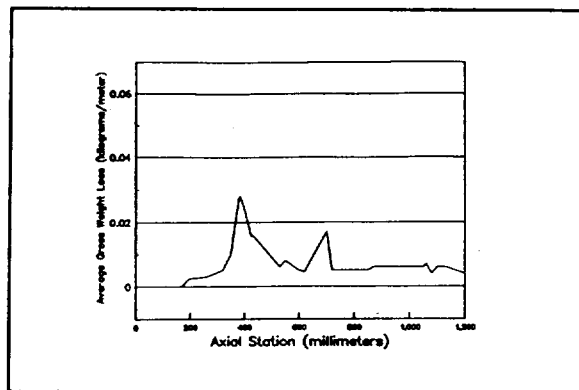


Figure 31 Axial Variation in the Surface Corrosion for LASL Replacement Element 56-339-93586 Post-Mortem

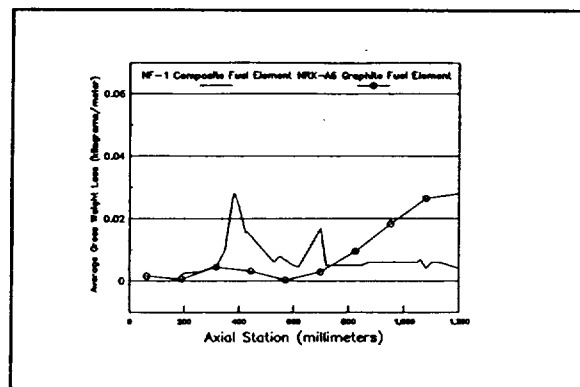


Figure 32 Comparison of Axial Surface Corrosion for NRX-A6 Graphite Elements vs. NF-1 Composite Elements

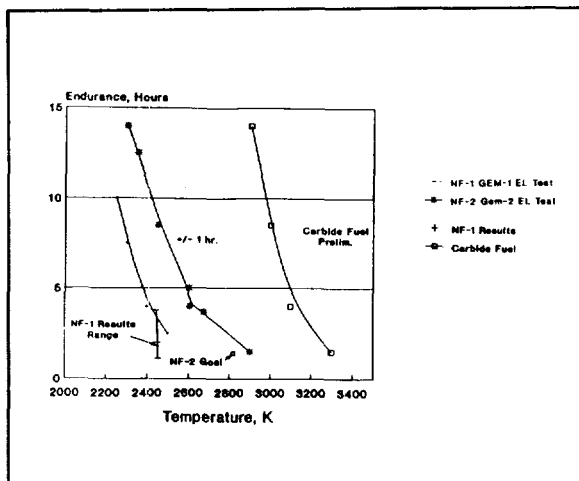


Figure 33 Endurance - Temperature Comparison, Composite and Carbide Fuels

elements. This did not account for the loss of actual fuel material which was about 2.5 percent (13 grams carbon loss in elements weighing about 500 g.). The fission product loss from the fuel elements to the scrubber in NF-1 was approximately one percent, as predicted. NF-1 operated at an average exit temperature of 2444 K for a total of 108.8 minutes. Higher temperatures would be expected to increase the releases. The fission products released to the environment were essentially zero in the nuclear furnace tests, when the charcoal filter was operated cryogenically (Ref. 41).

Carbide: A third ROVER fuel element type was the solid solution carbide. The potential capability of this fuel is also indicated on Figures 33 and 34. This fuel type offers attractive performance potential, if the obvious problems with fabrication, high CTE, lower thermal conductivity, higher element-to-element friction, and high modulus of elasticity can be accommodated. Research on carbide fuels was carried to the point of making and testing single-hole hexagonal "spaghetti" elements in the Nuclear Furnace. It was found to be very difficult to make full-size 19-hole elements of this type due to bowing during the sintering process. The carbide properties also lead to high thermal stresses; nevertheless, the NF-1 test results were relatively good. The power density in NF-1 was about 4 MW/liter. While cracking occurred in the fuel elements, the carbon loss increased only in proportion to the increased exposed surface. More work may produce acceptable fuel elements of this type. Higher

completed when the program was terminated.

Fission product release is also an important issue for nuclear rocket fuel elements. Considerable efforts were aimed to limit this release and on measuring the release during the NERVA tests. The release is strongly affected by temperature (Ref. 61). For the beaded graphite fuel elements, just below the bead degradation temperature of 2470-2570 K for duplex beads and 2570-2670 K for triplex beads, the release was about 5 percent; at about 2770 K, the release was about 35 percent. In actual reactor tests, for example, NRX-A6, the release was about 0.8 percent based upon gross gamma

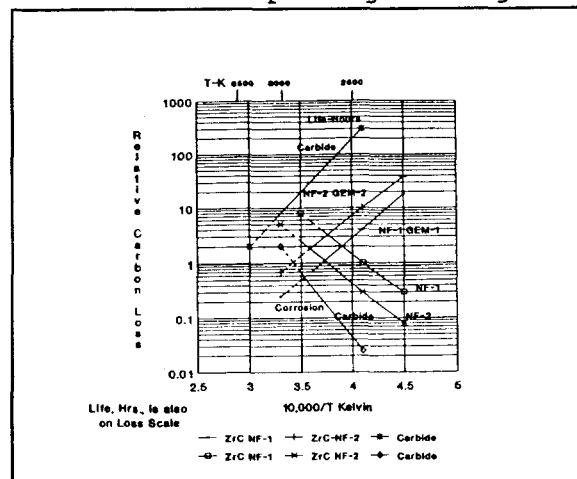


Figure 34 Carbon Diffusion to Hydrogen

density, higher critical masses, a shift towards fast neutronics, and increased weight are additional issues for this type fuel. These may be offset by the increased performance potential. Also, other reactor concepts may be conceived that can take advantage of the unique properties of carbide fuels. The performance estimates shown in figure 6 for carbides assumes the cracking problems can be overcome, and appear to overlook the higher mass of the carbide elements.

4.2.3.1.1.2 Cermet Fuel Reactors

In parallel with the NERVA/ROVER activities, there was extensive work in the nuclear airplane program on CERMET fuel elements at NASA LeRC, Argonne National Laboratory, and at General Electric (the 710 Program was designed for 1890 K, but elements were tested at 2800 K for 48 hours). General Atomics developed wire fuel (see Ref. 44) and General Electric developed prismatic fuel element approaches using cermet fuel cladding (Ref. 43). One of the prime attributes of the cermet clad fuel elements is that they may contain the fission products produced in the fuel; however, this containment will likely be affected by cyclic exposures at high temperature. The tungsten must be stabilized against grain growth which would permit uranium and fission fragments to escape along grain boundaries. Considerable effort was applied to stabilize the grain growth by additives, with some success. Figure 35 shows the fuel release for some of the tests, while figure 36 shows some of the improvements made possible with stabilizers (ref. 62-63).

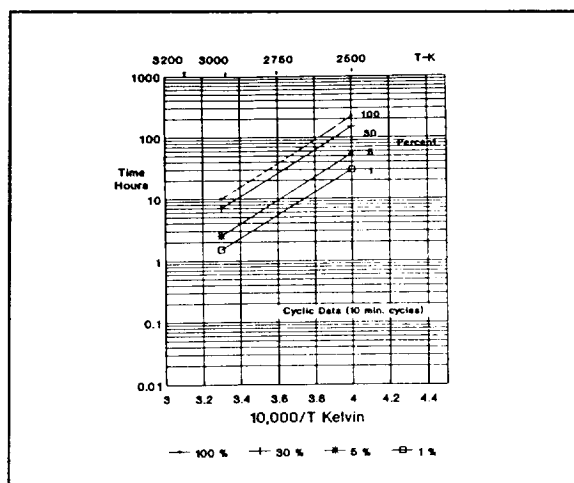


Figure 35 Fuel Loss from Tungsten Clad Fuels as a Function of Temperature

The refractory metals, such as tungsten, are affected very little by hydrogen. In addition, tungsten has the lowest vapor pressure of all of the potential rocket reactor fuel materials. However, the density is high and the nuclear properties are not favorable. Because of this, LeRC pursued the design of water-moderated tungsten reactors, (see Ref. 48), and evaluated the use of isotopes of tungsten to lessen the neutronic effects involved. Argonne National Lab pursued the non-moderated fast tungsten reactors, General Electric pursued the prismatic CERMET configuration, and General Atomics studied the wire core

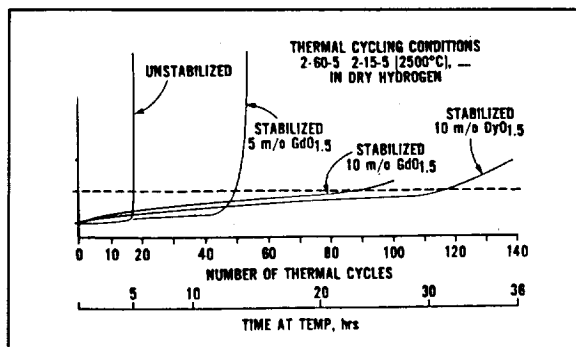


Figure 36 Stabilizer Effect on CERMET Fuel Loss

concept, as described earlier. The advantage of the wire approach was the increase in surface area density in the fuel bed and the additional degrees of freedom to space the wires as contrasted to packed beds, as well as the option of varying fuel loading throughout the reactor to maximize heat transfer rates. Plate, concentric ring, hexagonal prismatic, and wire fuel element types were all pursued. The hexagonal fuel elements were supported in tension. Reference 62, the ANL final report on their tungsten rocket reactor work stated: "The results of the refractory metal fast reactor technology program were encouraging. It was shown that fueled cermet clad with stabilized tungsten can be fabricated and will contain fuel for times well in excess of 50 hours at 2770 K. Tests in high pressure, high speed hydrogen demonstrated that the results of these tests seem to be valid for test pieces which simulate actual fuel element geometries." Fairly reasonable reactor designs were prepared but full scale rocket reactor tests were not completed.

A significant number of critical experiments were done at ANL and at GE on cermet reactors, and significant fuels developments were accomplished, including successful severe in-reactor thermal shock tests in the TREAT reactor (Ref. 63). The primary focus of the cermet fuels work was uranium oxide fuels in refractory matrices, clad with refractory cladding, usually, tungsten-rhenium. Stabilizing the refractory materials against grain growth was the major technology issue, and significant progress was made (see figure 36).

4.2.3.1.1.3 Particle Bed Reactors

There was some development work on particle bed reactors (PBR) at the Brookhaven National Laboratory during the time period of the ROVER/NERVA program. However, some more recent development of the PBR concept has been reported (Refs. 15,64,65). There are five main design aspects in PBRs:

- (1) the particle beads themselves,
- (2) local flow matching in the particle bed with the local power generation, with a controlled geometry "Cold Frit",
- (3) the very high temperature "Hot Frit" retainer for the particles,
- (5) the in and out flow passages to accommodate the "folded flow" paths, and
- (5) moderators designed so that the desired particle bed volume, from a thermal-hydraulic standpoint, can also contain the critical mass.

Since the design is so tightly "tuned" and its performance so affected by all of these PBR features, each of these topics will be discussed in the following section.

Fuel particles or fuel beads are small spheres in which the nuclear fuel is in a central kernel surrounded by a porous layer to provide space for fission gases, (see Fig. 8). An alternative is to use a low density fuel kernel to provide the space (Ref. 66). Additional layers provide strength, diffusion resistance, and corrosion resistance for the particle. Uranium carbide has been suggested for the fuel kernel. The other layers are usually a high density pyrolytic graphite layer, followed by protective coatings of carbides such as zirconium carbide. The coating thicknesses are comparable to those in NERVA. Other coating materials and processes may be feasible. (This improved particle bead may also be an effective fuel for a beaded graphite NERVA-derivative "fast track" fuel element to be discussed later, which when combined with an improved coating for the axial coolant channels, could provide superior fission product retention properties).

One important aspect of the PBR concept is that the particle outer surface is in direct contact with the hydrogen and, therefore, subject to carbon depletion corrosion that occurred in the NERVA fuel elements, which were coated with the same general types of coatings. Thus, the coating corrosion is likely to be increased in rough proportion to the surface area. However, the NERVA/ROVER surface corrosion data may not be directly applicable. Additional testing will be required to verify the corrosion resistance of these fuels. The high vapor pressure of ZrC may also be a concern. There is always the possibility that new coating forms can be developed, and these aspects will require attention in the future in both NERVA derivative and PBR development.

The design of the particle bed reactor must be a tightly "tuned" design, where the flow of hydrogen must be as closely matched to the local power density as possible, so that uniform particle temperatures are obtained across the hot exit of the bed. This maximizes the obtainable hydrogen temperature for a given maximum permissible particle temperature. The method of flow control to accomplish this uniform temperature distribution is a major uncertainty. The flow control system employed must account for any redistribution of flows which could occur due to the tendency for the flow to seek the least resistive path; this is a classic laminar flow instability problem, that has been extensively studied (Ref. 67). This latter issue may not be as difficult in thin PBR beds as it might be in thicker beds, such as a pebble bed reactor, which uses thick fuel beds. However, in the end, the maximum particle temperature in the reactor will be determined by deviations to the ideal match of flow and power. Adequate safety and reliability margins to ensure reactor integrity may severely limit the performance of this concept.

The flow-power match issue may be adequate at one "design" power level, but at off-design points, deviations must be accounted for. Flow stability is also required at off-design conditions as well, so that a run-away temperature excursion condition does not occur.

The hot frit and cold frit that bind the fuel particle bed offers significant design challenges. The hot frit will probably be subjected

to compressive loading, experiences the highest gas and material temperatures in the reactor, must be porous but not permit particles to escape, must not be subject to clogging, and the two frits must keep the bed confined to prevent particle redistribution; there should not be any adverse chemical or excessive load interactions with the particles. It would also be desirable if the particles do not stick together so that minor adjustments in particle location can be made to accommodate differential temperature distribution, temperature soak-backs, and so forth, without creating bypass flow passages.

In order to minimize engine mass, moderator materials are used to "moderate", or "thermalize" - the neutron spectrum in the reactor to thermal energy levels. The particle bed reactor is a heterogeneous reactor, in which the fuel and the moderator are separate. Moderator and the necessary supporting structure have a major impact on the effectiveness of the PBR design. The moderator must have good moderating properties which means that hydrogenous materials are preferred. The separate moderator and fuel bed causes neutron flux peaking on the moderator side of the bed. The core structural materials must be chosen to account for their neutron absorption properties, and must be isolated from the hot portions of the core, or cooled by the low temperature incoming propellant. The moderator and core structure must also be designed to account for temperature soak-back conditions during shut-down. These are some of the design issues which must be examined for a man-rated SEI PBR design.

4.2.3.1.1.4

Low Pressure Concept

The fuel in the low pressure concept could be particles or conical plate type fuel elements (Ref. 15, 46). The particles are assumed to be similar to those assumed for the PBR. The conical plates could be solid solution carbide conceptually similar to those proposed for the DUMBO concept. One virtue of the conical approach is that the flow passages are defined and not subject to "laminar-flow stability" deviations such as may occur in the PBR and PELLET beds, where the flow path is not defined. By using the proposed spherical core configuration shown on figure 14, with radial fuel assemblies embedded in a beryllium core structure with ZrH for moderation, a two-region fuel bed is proposed wherein a cooler layer of ZrC coated particles and a hotter layer of HfC (Hf-180) coated particles would be used. This may provide an increased exit temperature capability, to maximize the dissociation phenomena, if a method of loading the fuel particles in the bed can be developed.

There would be a central inlet cavity in which a control rod could function for redundant control (the low pressure concept is proposed to operate on hydrogen reactivity alone, without the need for control rods or drums). As in the PBR, there would be cold and hot frits to retain the particles. The cold frit is proposed to be made of zirconium, and the hot frit of ZrC foam. The exit passage would surround the spherical core. The fuel concepts involved, then, are particles with ZrC and HfC coatings and suitable solid solution carbides. The favorable neutronics may make possible the use of the higher temperature refractory carbides,

such as HfC.

4.2.3.1.1.5 Pellet Bed Reactor

This concept, shown in figure 13, uses one centimeter diameter pellets coated with ZrC in an annular reactor. The pellets are made with particles embedded in a graphite matrix in a coated sphere. The concept uses inward radial flow, has hot and cold frits, and has radial and axial reflectors. Most of the issues of the PBR also apply to the Pellet Bed concept. The principal problems seen with the design are, (1) the difficulty with matching flow and power distributions in such a thick bed, (2) the "laminar flow instability" issue discussed above for the PBR concept, and (3) the high velocity gas flow at the core exit plane.

El-Genk, (Ref. 45), discusses some of these issues. TRISO fuel particles, (Ref.68), developed for the terrestrial power HTGR program, are proposed for the PELLET Bed reactor. El-Genk found that axial conduction heat transfer and axial flow must be considered in an analysis of the PELLET Bed, and that orificing of the hot frit was critical to flow matching and power distribution. The laminar flow instability issue was not discussed.

4.2.3.1.2 Materials

This section discusses key materials issues for the types of reactors being considered for SEI NTP reactors. The Nuclear Fuels and Materials Panel addressed the NTP materials issues in some depth, and a summary of their findings is presented by Cooper in reference 69. Cooper concludes that the development and qualification of carbon-carbon composites for large complex structural applications and innovative coating systems capable of protecting these carbon-carbon structures from high temperature hydrogen attack will be required to reach the high performance, high temperature goals of the SEI missions.

Some of the common materials problems for all the concepts include:

- materials must be producible and cost-effective
- very low to very high temperatures in hydrogen,
- high performance applications (high stresses, high neutron environment, corrosive environment, and so forth),
- thermal and mechanical transients
- high reliability and safety requirements

4.2.3.1.2.1 NERVA Derivative Reactors

Aside from the fuel elements themselves, other reactor core components are: the other cluster components (the insulated hydrogen cooled tie tubes, the insulation, the cluster support block, the sleeve-type inlet orifices, the orifice plate and the inlet-end poison material), the peripheral unfueled elements which round-out the core, the lateral support system (which consists of the core barrel assembly,

the graphite support pins and the flat springs for core centering and retention of the seal rings which provide lateral pressure to bound the core), the reflector and control drums and their actuators, the core support plate, the internal shield, and the pressure vessel.

The earlier NERVA design included plastic coated poison wires that were inserted in the flow passages to provide sub-criticality safety in the event of a water submergence as a result of a launch accident. These poison wires would have to be removed, robotically or manually on-orbit, prior to startup of the reactor for inter-planetary flight.

The NERVA design also included extensive instrumentation within the reactor for control and diagnostic purposes. The design did not include the instrumentation, controls, health monitoring, diagnostics and related computer control equipment envisioned for an SEI mission in which the vehicle would be capable of completely autonomous operation, with or without astronauts on board, programmed to complete the mission as planned, and capable of taking correctives measures as required, to enable contingency options to ensure astronaut safe return, for example. This will be a critical design and technology issue for whichever system is chosen to perform the SEI missions.

Some of the NERVA component and system materials issues are described below:

Component/Subsystem:	Material, Issues, Comments, Issues:
1. Tie Tube	<u>Inconel 718</u> , satisfactory, free of hydrogen embrittlement, strong, fabricable
2. Insulation	<u>Pyro Graphite</u> , suffered some edge corrosion, foamed carbide is possible replacement
3. Support Block	<u>Graphite or composite</u> , subject to thermal stress cracking of coating in transients
4. Inlet Sleeve Orifices	<u>Aluminum</u> , (includes filter screen) more sizes could reduce temperature deviations
5. Front-end poison	<u>Gadolenium</u> , satisfactory
6. Peripheral filler elements	Same as fuel type, satisfactory
7. Lateral Support System	<u>Graphite</u> , satisfactory
8. Core Support Plate	<u>Aluminum</u> , satisfactory

9. Internal Shield	<u>Boron-aluminum-titanium-hydride</u> requires optimization, consider external shield only
10. Reflector	<u>Beryllium</u> , generally satisfactory, subject to cracking, difficult machining
11. Control Drums, Actuators	<u>Beryllium with boral poison</u> , Actuators plates were generally satisfactory, subject to thermal bowing in transients, providing redundancy is a controls issue
12. Core Support Plate	<u>Aluminum</u> , satisfactory
13. Pressure Vessel	<u>Aluminum</u> , satisfactory, may be better, lighter materials, but must be qualified
15. Poison Wires	<u>Teflon coated</u> , generally were satisfactory, requirement must be determined
16. Instrumentation	<u>Varied</u> , need improvements as discussed above, requirements must be defined, new materials may be required for cables, insulation, sensors, and semi-conductors

The need for mass optimization implies that each of the above component designs and materials selections should be reviewed for present SEI applications. The primary driver for reactor mass is the volume and the density of the materials used. The core volume is largely controlled by the core power density and heat transfer effectiveness, which is largely a fuel element issue. It must be noted that the PHOEBUS core power density was several times that of NERVA. Advanced materials should be considered to improve the mass of the NERVA reactors. The issues of inadvertent or accidental reentry, and final engine disposal must be addressed for this, and for other concepts.

4.2.3.1.2.2 CERMET Reactors

The CERMET reactors have not had as much development as the NERVA derivative type, thus, the designs and materials selections are not as well known. In general, the designs of the prismatic CERMET versions are quite similar to NERVA, with the exception that most of the core structure is made of refractory materials like tungsten-rhenium. The movable reflector and the control drums, if used, are made using beryllium oxide instead of beryllium. Reference 64 provides conceptual designs in considerable detail of both 200 and 2000 MW power levels.

This covers the likely range of interest and showed that concepts were feasible. General Electric proposed a CERMET prismatic fuel element concept at the NTP workshop as noted in Section 3.1.4.

A significant design change in the prismatic cermet designs, stemming from large flux gradients at the core edge, led the designers to propose a preheater annular portion of the core, in which these gradients could be managed since the coolant temperatures were lower in the preheater annulus. This also aided in handling power density scalloping at the controls drums. A liner was then required to separate the two core zones. However, from a materials standpoint, the major issues stem from the general use of refractory materials for structures in the fast reactor versions.

The WIRE CORE and Tungsten-water-moderated reactors would have material issues that are similar to the other cermet approaches. Both concepts would require improved joining techniques. Specific reactor designs for SEI applications have not been made. The reflector, controls, and pressure vessel materials issues are also similar. In all cases, advanced materials may contribute to needed improvements in reactor mass.

4.2.3.1.2.3 Particle Bed Reactors

A large number of materials technology issues were identified for the PBR concepts at the NTP workshop. This advanced concept incorporated advanced materials throughout the concept proposed, in an effort to obtain the minimum reactor mass while maximizing reactor power density and heat transfer effectiveness. For example, ceramic matrix composite (CMC) rotor blades are proposed for the turbopump. Much development will be required to validate this technology at the temperatures involved. Similarly, a lightweight CMC or carbon-carbon pressure vessel is proposed. Again, detailed design and testing of materials at the environmental conditions expected, involves a major development program. The potential benefits of using very advanced materials throughout the reactor used were noted at the workshop (Ref. 15), but the technical risk involved was also noted and must be balanced against the potential benefits and safety implications for an SEI mission. Since the high thrust-to-weight claimed for the PBR is not a major driver for the SEI missions, some of these advanced developments may not be required.

4.2.3.1.2.4 Low Pressure Reactors

The large one meter diameter spherical beryllium core support structure is the major non-fuels materials issue, (see Fig. 14). The other issues are similar to the PBR, with the hot frit probably being more difficult because of the higher temperatures and possible enhanced corrosion effects of dissociated hydrogen. The annular exit passage has a very large area, and the outer pressure vessel may have to be cooled, considering the enhanced heat transfer properties of hot hydrogen in a possible recombination zone.

4.2.3.1.2.5

PELLET Bed Reactor

The material issues in the PELLET Bed reactors parallel those in PBR and Low Pressure Concepts. The end reflectors will cause increased power density gradients in adjacent regions, and it may be difficult to match flow in these areas. However, the end reflectors will tend to flatten the axial power profile which should help in the flow-power matching for such a thick bed.

4.2.3.1.3

Nozzles

Significant cooled nozzle technology improvement has occurred since the conclusion of the NERVA program. The current Space Shuttle Main Engine, SSME, operates over 3100 K, with throat heat flux capability of 100 btu/in²/sec - four times greater than NERVA heat flux designs. In the SSME nozzle, coolant channels are milled directly in high strength copper alloys. Even more advanced nozzle cooling techniques are being studied in the National Aerospace Plane Program (see, for example, Ref. 70 and 71). Nozzle computational methods have also improved significantly. Codes such as TDK, (Ref. 72), are expected to be particularly useful in the design and evaluation of NTR nozzles.

Uncooled nozzle skirts for SEI applications are expected to present technology issues. Area ratios up to 500-to-1 are proposed to maximize specific impulse. CMC or carbon-carbon, uncooled nozzle extensions have been suggested. For a 75,000 lb engine, this could result in a nozzle extension over 50 feet long and over 14 feet in diameter. Although small uncooled nozzles are made for various applications, there currently are no known manufacturing facilities for nozzles of the size suggested. Structural issues such as vibration and in-space assembly must be addressed; the 500:1 area ratio may prove to be too aggressive.

The cooled-uncooled nozzle interface is expected to be a critical design issue because of the temperature differences involved and the consequences of a failure at this joint. This issue is further complicated by the assumption that this interface probably could not be tested in the full system ground test facility. Development and flight certification of this interface will be an important activity. Protecting the uncooled extensions inner surface from hydrogen corrosion may also be a significant problem.

Bell nozzles are not the only nozzle configuration suggested for the SEI missions. Alternative concepts, such as aerospike, plug and truncated plug nozzles, could offer attractive packaging options for an NTR vehicle, with minor performance penalties, (Ref. 73). A study of nozzle alternatives will be required to evaluate these options for SEI missions.

4.2.3.1.4

Turbopumps

State-of-the-art turbopump technology has also advanced significantly since the NERVA program termination. The SSME turbopump is currently

capable of pressures from 3000-7000 psia. An extensive database of turbopump designs developed since NERVA will probably support the necessary integration of a custom-designed turbopump for selected reactor designs. It may also be possible to utilize an existing design, perhaps down-rated, to save the development cost of a custom-designed pump. It is expected, however, that modern CFD analyses and structural design techniques and technology should result in reduced turbopump weight, together with improved reliability of this critical engine component.

4.2.3.1.5 Instrumentation/Controls

Reactor instrumentation and controls (I&C) technology, as currently used by the power and research reactor community, was largely developed in the 1950s and early 1960s for the light water power generation reactors. Many of these instruments are not relevant to today's proposed advanced space reactors, nor are there adequate reactor control schemes that will be necessary to operate these systems autonomously, and to ensure the safety of SEI astronauts. NASA has developed advanced control theories and approaches since the SNAP-10A program, but these advances have not been demonstrated on reactors.

The development of I&C technology must proceed in parallel with the development of other engine technologies and engine design activities, since I&C integrates the operation of the entire system. A summary of some of the important I&C requirements are shown.

Sensors are required to directly measure parameters of interest whenever possible:

- Sensors must operate accurately for several hours (3-10), for multiple cycles, at high temperatures and in a high radiation environment.
- Advanced temperature (coolant and materials), pressure, flow, and position sensors are needed.
- Radiation flux detectors, in and around the core, are needed, particularly a neutron start-up detector.
- Instrumentation cables that are insensitive to gamma heating are needed for sensors near an NTP core.
- Thermocouples are relatively unreliable, especially in the core environment; an advanced temperature sensor that is both simple and reliable is required.

A new generation of electronics will be required, that are radiation hard (2-3 orders of magnitude improvement is required), and survivable at much higher temperatures (currently 125-250 C, need to go to at least 250-300 C). Without these improvements, large mass penalties will be required to shield these devices. Higher temperature electronics will

also reduce the size of electronic waste heat rejection systems. Electronic devices must operate from -55 C to greater than 300 C. Redundant circuits must be developed to eliminate single event upset (SEU) problems and eliminate single point failures.

A new generation of radiation hard, SEU-proof computers must be developed for NTR control systems. Artificially-intelligent controllers, incorporating signal validation and verification, advanced control laws, health monitoring and contingency planning, must be developed. There are certainly tradeoffs between this technology development and shielding options, when today's "radiation-hard" technology is considered.

4.2.3.1.6 Conceptual Designs

Concept summaries were presented at the NTP workshop (Ref. 15) and were summerized in Section 3.0. Very limited conceptual design work has been done since the end of the ROVER/NERVA program. Current design and analysis computational tools should permit much more accurate designs, analyses, and trade-offs.

4.2.3.2 NTP Technology Test Plan

The NTP panel emphatically endorses a strong systems design and engineering activity, in parallel with the research and testing activities. Thus, an integrated modelling, analysis and design effort, a fundamental research and technology validation test activity, and appropriate facility development activities should form the foundation for the technology development project.

The following section will focus on definition of the technology validation test requirements and objectives. Parallel modelling and analysis efforts will be discussed briefly, when appropriate, and facility needs will be discussed. The efforts of the NTP panel should be considered only a first step along a very long technology development path, and these test plans must be up-dated and improved regularly to reflect progress and terminate efforts on "dead-end" efforts. No attempt will be made to identify specific test facilities for the tests described; the test facilities panel has developed an extensive database on existing facilities that may be applicable for these tests, and facility evaluation teams in 1992 will attempt to recommend appropriate facilities for the tests required. Similarly, a "modelling" evaluation team will assess existing models and requirements in 1992, in an effort to integrate appropriate modelling efforts in the project from the beginning.

The NTP Summary Test Plan was shown on page 12 in Figure 2. The following sections will address each of the elements of the test plan.

4.2.3.2.1 Fuel Fabrication/Characterization

Given the background from the ROVER/NERVA program and other

development activities described earlier, and the evolutionary fuels strategy developed jointly with the fuels and materials panel, shown in figure 3 on page 13, and described in Section 2.2.3, the following observations and recommendations are made for the fuels fabrication and characterization activities. The three general categories of nuclear fuel which show promise for use in solid core nuclear thermal propulsion applications, in priority order are: prismatic NERVA-derivative fuels (starting with composite fuels and evolving to carbides), particle fuels (for possible use in PBR, NDR, or PELLET BED), and other CERMET fuels. These three fuel types cover most of the solid core NTP concepts presented at the NTP Workshop. This is illustrated below:

REACTOR CONCEPT	FUEL/COATING	FUEL FORM
ROVER/NERVA	UC-ZrC-C	Duplex
ENABLER, ENABLER II	UC-ZrC-C	Composite
Low Pressure Core	UC-ZrC	Particle
Particle Bed, PBR	UC-ZrC	Particle
Cermet Reactor	UO ₂ -W	Cermet
NIMF	UO ₂ /ThO ₂ -ZrO ₂	Particle
Wire Core	UN-W	Cermet
DUMBO	UO ₂ -Mo	Cermet
Advanced DUMBO	UC-ZrC-C	Composite
Pellet Bed	UC-NbC	Particle

The particle fuels and composite fuel types based on carbon or graphite or their compounds, whereas the cermet fuels have been based on a refractory metal surrounding oxide or nitride compounds of uranium. While many of the fuel development programs in the 1950s and 1960s were prematurely terminated because of funding decisions, they did serve to identify many of the key issues encountered and the testing required to provide resolution of these issues.

A key issue is the fabrication and development of defect-free forming of metal matrix-fuel components and defect-free coating-to-matrix bonding. This issue also includes means of inspection to show that these requirements have been met. Fabrication development and inspection technique development programs should be initiated on the most viable fuel-matrix-coating material combinations. Use of diffusion bonding, CVD and hot isostatic pressing are some of the fabrication techniques to be evaluated. New nondestructive inspection techniques such as acoustic, micro-focus x-ray and CAT scanning should be among those evaluated.

The overall objectives of this task are:

- (1) to recapture ROVER/NERVA fuel fabrication procedures for composite fuel (with improved coatings) and carbide fuels, (a faster option to be discussed later would start with an improved NERVA beaded particle fuel (perhaps with an improved particle and/or an improved coating);

- (2) to develop new fuels, fuel forms and coatings;
- (3) to develop improved fabrication procedures and processes;
- (4) to fabricate test fuels and fuel elements;
- (5) to demonstrate quality assurance procedures;
- (6) to develop a pilot plant for fabrication of test fuel elements;
and
- (7) to characterize the physical, thermodynamic and mechanical design properties of the fuels, including statistical data.

Requirements for this task include the capability for special nuclear material (SNM) handling, feedstock preparation, fuel form fabrication, particle forming and coating process application, extrusion, hot pressing, graphitizing, sintering, coating, brazing, welding, property measurement, production assembly line, and fuel element assembly.

4.2.3.2.2 Fuels Testing

The fuels testing needed for NTR fuels can be broken down into non-nuclear and nuclear fuels tests.

4.2.3.2.2.1 Non-Nuclear

Non-nuclear (or unirradiated fuel) test objectives include characterization of various fuels for chemical, physical, thermal and structural properties to provide design data for early screening and to provide improved fuel-coating combinations engineered to provide the characteristics required to perform the intended function.

Key technical issues with NDR and particle (carbon-based) fuels generally are coating integrity, coating and fuel life, and fission fragment behavior. Test plans to study fission fragment behavior is addressed in the next section. CERMET fuels present unique technical issues and these will also be addressed below.

Coating Integrity: Coating integrity is a key factor in protecting the fuel from corrosive attack by the hydrogen coolant, and providing a desired barrier to fission products. For a particle fuel, the coating must also provide some strength capability, to withstand the stresses on the particle. The issue results because of varying degrees of mismatch of coefficients of thermal expansion (CTE) between the coating and the fuel over which it is applied. The CTE mismatch can be influenced for particle fuels by intermediate layers between the kernel and outer coating, and selection of specific material compositions of kernel and outer coat. Should the mismatches in CTE be severe enough to cause the coating to have open cracks or, in the worst case, to actually spall off, the fuel kernel would be exposed to the coolant. This was evident in the NERVA test program, as described earlier, and a great deal of

effort was used to mitigate this effect.

Most fuel compounds for particle bed reactors are based on refractory carbides with either a single fissile carbide (i.e., UC_x , where x is between 0.8 and 1.98), or a mixed carbide to increase operating temperature (i.e., $(U, Zr)C_x$, $(U, Nb)C_x$, and so forth). With a reducing coolant, H_2 , these compounds are susceptible to stoichiometry changes and subsequent loss of material due to vaporization. Cracked or spalled coatings also cause a loss in particle strength which can result in changes in bed configuration due to denser packing or loss of material to the coolant flow. The outer coating is also one of the major barriers to release of fission products and cracking is deleterious to this function, as well.

As noted for particle fuels, coating integrity is also an issue for NDR fuels due to mismatches in CTE between the matrix material and the coating. It is also a function of the shape of the fuel form and the means of applying the coating on that fuel form to get a uniform coating with respect to thickness and composition. The temperature of the substrate when the coatings are applied is also important, as noted earlier. A significant amount of work was done to address this issue in the ROVER/NERVA program, and while significant progress was made, coating integrity (cracking) issues were not completely resolved.

Coating Life: Presuming that coating integrity can be maintained by elimination or mitigation of cracking, the life of the coating is another key issue. The life of the coating is affected by coolant erosion, coolant corrosion and diffusion phenomena. Due to the desired high operating temperatures, refractory carbides are generally used as the outer coating for the fuel. In particle bed and pebble bed reactor designs the outer layer is usually backed by intermediate carbon layers. The hydrogen coolant is reducing in chemical nature for all of the NTR concepts except perhaps NIMF. Coolant flow is usually very high through the bed due to thermal-hydraulic considerations. Because of these general characteristics, the outer coating may be eroded by the coolant flow, and corroded by the coolant depleting the carbon in the outer coating. Depending on the kinetics of the carbon removal and the diffusion of carbon from the inner coats (if present), the coolant may deplete the outer coating layers of carbon and result in vaporization of the metal constituents. Any one of these effects or any combination may thus have an impact on coating life somewhat independent of coating integrity due to cracking.

Coating life remains an issue for NDR concepts. Since the outer coating is generally deposited on a carbon matrix, however, loss of carbon from the coating may be less severe than in coated particles with no inner carbon layers provided. The diffusion kinetics of carbon to the surface may be sufficient to replace the carbon loss. Erosion effects should also be somewhat less severe because surface areas exposed to coolant flow are less, although flow velocities are considerably higher.

CERMET Fuel: Cermet fuels are different than particle fuel or NDR fuels, in that the major structural constituent is a refractory metal. Generally, tungsten, tantalum, rhenium, and molybdenum have been suggested, with either uranium oxide, UO_2 , or uranium nitride, UN, as the fuel. The fuel is clad with the refractory metal or alloy (usually combinations of the above refractory metals, plus possibly hafnium). The key issues with cermet fuel include fuel material swelling, fission product retention, neutronics issues (refractory metals have generally higher neutron absorption cross sections), grain growth and stabilization, coolant compatibility, and fabrication issues.

Fuel swelling due to high burnups may be an issue, (probably more important for NEP systems), because it leads to a loss of fuel shape and cladding bond (blisters, bubbles). This can result in closure of coolant channels and distortion of the fuel component and the core itself. This remains a key issue area to be defined. This issue is also closely linked to fission product retention. If fission product retention becomes a requirement, then the fission product effect on coating integrity must be understood. If fission products can be vented, that alleviates the fuel swelling issue and associated distortion. The issue of differential CTE between matrix and fuel material remains.

Fast reactor neutronics are significantly different than thermal or epithermal reactors. The use of refractory metals, especially major amounts of rhenium and hafnium, will require careful neutronics design of the reactor and may limit those options. Use of less neutronically objectionable metals should be investigated and perhaps the use of lower cross-section isotopes of the metals. At present, this remains a key issue insofar as reactor design is concerned. The critical reactor mass is also an issue, related to nuclear material safeguards.

Coolant compatibility of cermet fuels, especially in hydrogen at expected use temperatures in a nuclear environment, is also a key issue which should be a part of the test program.

Proposed Tests: Non-nuclear tests include phase relationship studies, coolant interaction effects, and CERMET-specific effects. On figure 3, (NTP Evolutionary Fuel Strategy), phase relationship studies are included in the effort entitled "Fabrication, Properties." Similarly, coolant interaction effects are included in the effort entitled, "Hot Hydrogen-Erosion-Corrosion-Life." This testing must be done for each of the three fuel types included in the "Fuel Strategy:"

- Prismatic Fuel (Thermal Reactor)
- Particle Fuel (Heterogeneous)
- Refractory Fuel (Fast Reactor)

Within each of these broad areas, the following specific test programs have been described.

Phase Relationships: The work in phase relationships should deal with the high temperature chemistry, thermodynamics and high temperature diffusion kinetics of the constituents in the fuel and the coatings used. The behavior of the uranium compounds and coating constituents in combination under anticipated (simulated) thermal gradients, and at expected operational temperatures, must be defined. Phase stability of the fuel and coating materials must be known to effectively design the coated fuels to withstand the time and temperature regimes desired.

Neutronics calculations and mission requirements should be used to limit the number of fuels and coating materials, specimens and scope of this experimental program. For example, there certainly is no point in looking at uranium contents much below or much above those required for criticality and power requirements. Neither is there much to be gained by looking at diluents or coating materials that are large neutron absorbers, or could not reach mission temperature requirements.

Coolant Effects: The experimental work needed to understand coolant effects could be closely coupled with the work on phase relationships since the effect of the coolant can alter the chemical composition of the outer carbide coating. This could thus change the chemical equilibrium of the coating and, thus, the driving force for movement of elements into or out of the coating, or through it. This effect of the coolant would be the so-called corrosion phenomenon where carbon can be selectively removed from the carbide outer coating. The effect of this phenomenon on the behavior of the overall fuel-coating combination, and the behavior of the compounds and elements inside the coating at expected thermal conditions of use must be understood. In addition, the erosion effect, if not coupled directly to the corrosion effect, should also be defined for different coolant velocities as a function of temperature and time. This will also include the effects of various hydrocarbons that will be present in the hydrogen after corrosion is initiated.

Storms, et al, (Ref. 74) has recently presented the results of analytical work at Los Alamos to understand the corrosion-life-temperature effects in both NDR and PBR reactor systems. This modelling work should continue to help guide and scope the experimental efforts, and to provide computational tools for system designers.

CERMET-specific Tests: High temperature testing of cermets will be required to determine temperature capability and compatibility of UN and UO_2 with tungsten, tungsten alloys, tantalum, and other high temperature cermet candidates for nuclear propulsion applications. Compatibility with other fuel matrix and cladding materials must also be assessed. It is expected that substantial progress has been made with cermet fuels since the early 1970s for the nuclear power industry and the nuclear Navy programs. Similarly, the top priority system for nuclear electric propulsion applications is a (lower-temperature) cermet, and joint, cooperative testing programs are anticipated.

A materials research test program will be required to improve the cermet matrix performance. The matrices developed for the nuclear airplane program seemed to be performance limiting. While melting was not substantiated, even at temperatures above the UO_2 melting point, core-cladding void spaces were filled with vapor-transported uranium and UO_2 , and fuel matrix cracking occurred due to incompatibility between fuel and tungsten coefficient of thermal expansion, and thermal cycling caused additional cracking due to the brittle nature of the tungsten in the cermet. Advances in CVD techniques, blending techniques, new alloys of tungsten to enhance ductility, and so forth, should be incorporated into this test program. Special attention should be paid to matrix materials with improved neutron absorption spectrums.

A fuel-matrix stress model should be developed and validated, that is based on test data, and incorporates fission product induced stress at anticipated operating temperatures. Data from past carbide and cermet fuel development and testing indicate that damage thresholds due to fission product buildup may be encountered at specific total irradiation durations. This data strongly suggests a relationship between the stress induced by increasing fission product concentrations and the strength of the fuel matrix structural material at temperature. Development of a model to predict this stress for candidate materials and to predict total irradiation time prior to onset of fuel damage would be valuable in assessing new candidate fuel materials without extensive and expensive in-pile testing. It is expected that this issue will also be very important for a nuclear electric reactor, because of the much longer life and, consequently, higher fuel burnup for those systems.

4.2.3.2.2.2

Nuclear

The effort in this task describes the efforts indicated on figure 3 - Fuel Strategy - as the "Fission Fragment Release-Corrosion," to understand the added effect of radiation on the corrosion-erosion characteristics of the various fuel types in small scale tests in existing experimental reactors.

Fission Product Retention: The main issue being addressed in this effort is the capability of the various fuel concepts to retain fission fragments, as a function of fuel life and operating temperature.

In particle bed fuels, fission product retention is claimed by coating the fuel kernel with a layer of porous graphite (providing a place for gases), and then providing a high-strength outer coating to encapsulate the gases. Retention of fission products is thus dependent on coating integrity, coating life and diffusion kinetics of the fission products through the coatings. The effectiveness of a concept to retain fission products is generally poor with cracked coatings, and best with diffusion-controlled release. The fission product generation is a strong function of fuel burn-up, and hence, power and burn-time. Coating cracking is certainly influenced by the duty cycle of the reactor (number of on-off cycles). Test programs to define fission product release characteristics thus must be somewhat concept-specific.

For the NDR fuel elements, the outer coating on the matrix material is the final barrier to fission product release. The key issues are the same as the issues described above for PBR fuels: coating integrity, coating life, and the diffusion of fission products through the coating.

A possible combination of the best PBR fuel particle, a fuel particle with possible fission product retention capability, with the proven NERVA fuel element technology, (the PBR particle would simply replace the duplex fuel bead), could result in a relatively near-term engine with the following advantages:

- good fission product retention capability, utilizing an advanced particle fuel
- minimum technology development, minimizing cost and development time
- compressive stresses on the particles would be virtually eliminated,
- engine performance, while certainly not as high as claimed for PBR, would be better than NERVA tested (2350 K), and could be as good as a composite fuel NDR (up to 2700 K).

Protection of the graphite substrate with an appropriate coating combination remains an issue, but may be somewhat easier in the temperature range from 2500 to 2700 K.

The behavior of fission products, their effect on coatings and their release fractions as a function of time at temperature, use temperature and burnup (fission product inventory) must be defined for each fuel. These tests will provide the data required to make intelligent selections regarding fission fragment release rates, performance penalties associated with minimum releases, and fundamental safety and reliability data. One of the recommendations of the Nuclear Safety Policy Working Group is that fission fragment releases should be "as low as reasonably achievable." These tests will help to determine achievable release rates, and will provide the data necessary for policy makers to select fission fragment release requirements for an NTP system. The milestone indicated on figure 3 as, "Safety Reqmt?" represents the determination of the release requirement, and will undoubtedly have a major impact on the selection of the nuclear thermal propulsion systems to be developed.

The key to the usefulness of this data is the achievement of the anticipated use temperature and heat generation rates for the concepts proposed to meet the mission requirements. It must be noted at this point that it will be very difficult, if not impossible, to accurately simulate the PBR reactor conditions in an existing test reactor. Test reactors are limited in their temperature capability, neutron flux densities, as well as their neutron spectrums available at the test locations. Obviously, no single test reactor will be able to provide

the appropriate test conditions for (1) a thermal reactor with power densities typical of an NDR, (2) a heterogeneous reactor such as the PBR with extremely high bed power densities, and (3) a fast flux CERMET or WIRE CORE reactor. The new "Fuel Element Tester" or "Nuclear Furnace" to be discussed in a later section, may be the only facility (or facilities) that can accurately simulate the real operational conditions for these reactor types.

In-reactor testing in existing facilities should be performed in a hot hydrogen environment to address compatibility issues, as well as thermal stress issues as early as possible in the program. Long duration tests can also provide information on fission product damage and fission product release data that will be required for the "nuclear furnace" safety approval process. This type of testing can also provide information on the ability of fuel element designs to withstand operational transients.

The existing experimental reactors where this type of testing might take place include:

- a. ATR, Advanced Test Reactor, at INEL,
- b. FFTF, Fast Flux Test Facility, at Hanford,
- c. EBR-II, Experimental Breeder Reactor II, at ANL-West,
- d. HFIR, High Flux Irradiation Reactor, at ORNL,
- e. PBF, Power Burst Facility, at INEL,
- f. TREAT, at ANL-West,
- g. and, possibly the EWGR, in the USSR.

A major nuclear test planning and facility selection activity must be accomplished early in the technology development project to have a clear understanding of what can be learned in existing reactors, and what must be accomplished in new facilities designed specifically for the demanding test requirements of an NTR system.

As noted earlier, CERMET fuel development for high temperature application is limited, but previous data are encouraging. Fuel tests at temperatures up to 3270K, and thermal cycling tests for many cycles at lower temperatures conducted during the General Electric 710 program, provide some indication of extreme temperature capability Ref. 43). Nuclear tests conducted during the ANL nuclear rocket program to determine cermet fuel resistance to thermal shock indicate that these fuel compounds are exceptionally strong. However, test data are limited. There have been no tests of these fuels both at high temperature and in a nuclear environment. The following nuclear test program would be required. First, however, an appropriate test facility must be modified or built.

High temperature, high flux testing in a hot, flowing hydrogen environment should be performed. A high temperature test facility capable of up to 3500K, hot flowing hydrogen, and neutron flux similar to levels projected for high power density nuclear rockets is needed to settle conflicting claims from carbon and cermet fuel proponents. There

may be an existing test reactors that may be modified for this purpose. This facility would be used to test the fuel and cladding behavior in terms of swelling, fission product behavior and lifetime considerations in hot hydrogen. This type of testing may be considered as a proof test for overall performance of a specific fuel configuration, as well as a specific test to define swelling behavior as a function of fuel (UO_2 , UC_x , UN) matrix and clad materials, fission product behavior (especially in regard to release mechanisms) as a function of the above materials, and effect of hydrogen on clad properties (especially embrittlement).

4.2.3.2.3 Materials Testing

Quite a large number of materials issues were identified earlier in the state-of-the-art discussion, and in the discussions of each of the NTR concepts. Coating integrity and coating life remain top priority efforts required in the fuels technology area, while high temperature fuels also are required to increase performance. More importantly, however, statistical data on all of the fuels and materials to be used in an NTR system must be in-hand or must be developed, to enable probabilistic risk assessment for effective risk management. However, the project can not afford to develop these databases for materials that will not be used, so this effort must be guided by conceptual designs and systems engineering activities, to focus on appropriate materials.

4.2.3.2.3.1 Non-Nuclear

Non-nuclear materials testing will start with currently identified material issues, and will continue throughout the project to provide the appropriate statistical data required, based on the current conceptual designs and subsequent detailed hardware designs. These data will be critical to ensure approvals for safety analyses, environmental impact statements, and ultimately, for flight approvals.

4.2.3.2.3.2 Nuclear

Similarly, nuclear material testing will be required in the high radiation environments that will be experienced by the components of a nuclear engine. Any material that is required as part of an engine design, and is not covered by existing nuclear material databases, such as ROVER, NERVA, SNAP, SP-100, the nuclear power industry, or the nuclear Navy databases, will require extensive radiation testing. Radiation testing in existing reactors can be performed early, subject to the performance limitations of the existing experimental reactors. Some anticipated problem areas involve:

- a. embrittlement in a LH_2 /radiation environment,
- b. moderator, shield, control drum, and so forth, dimension changes due to irradiation,
- c. electronics, sensor damage due to irradiation,

- d. bearing surface coating deterioration from irradiation, and
- e. fiber composite degradation in a radiation field.

4.2.3.2.4 Fuel Element Tests - Existing Reactors

In-reactor testing in existing facilities is limited by the ability of research and test reactors to obtain the power densities necessary for nuclear thermal propulsion systems. Existing research reactors could be used to duplicate element performance for the NDR reactor concepts, and possibly some other relatively low power densities. No test reactor exists in this country that can duplicate the test conditions required for the PBR concept, and no "fast spectrum" reactor exists, that the authors know about. However, this type of test is the only way that full or subscale fuel elements can be tested in the near term, in an existing reactor, in a nuclear environment, heated to full temperature conditions. Therefore, the major goals of these tests should be an early test of full or subscale NDR or other low power elements to full temperature, power and duration limits, as early as possible in the development program. These tests should be performed in a flowing hot hydrogen environment to address compatibility issues, as well as thermal stress issues. Long duration tests can also provide information on fission product damage and fission product release data that may be required for the "nuclear furnace" safety approval process. This type of testing can also provide information on the ability of element designs to withstand operational transients. It should also be mentioned that significant hydrogen compatibility and thermal stress data were obtained in an electric furnace for the elements developed during the NERVA program, and this type of testing should be used to perform element and coating screening, prior to testing in a test reactor (Ref. 75, 76).

4.2.3.2.5 Fuel Element Tests - New Element Tester

A "Nuclear Furnace-like" facility (Ref. 41) will be required to test either very high power density fuel elements, or "fast" reactor fuel elements, in prototypic conditions. This may actually be two separate facilities to satisfy the requirements of both of these types of reactors. This facility should provide full power density, temperature, coolant pressure, and full flow rates for fuel lifetimes comparable to design run times (or more), in order to qualify fuel elements. It was observed during the ROVER/NERVA program that fuel element performance was the limiting component in nuclear rocket engine performance. After building a number of reactor test assemblies that demonstrated that a hydrogen cooled nuclear rocket engine could be made to work as designed, a test assembly was designed that could provide prototypic conditions for individual elements, but required far fewer elements to go critical. This test assembly was called the "Nuclear Furnace". It seemed to have strong economic advantages for fuel element development and qualification, but the program was terminated before the planned testing could be completed. This facility also demonstrated the effluent cleanup system that will be required for engine testing. The

requirements for this a test facility of this type will be discussed in a later section of this report.

The "Nuclear Furnace-like" facility should be an integral assembly capable of including multiple test elements in its core. It should operate at the prototypic power conditions. This will probably be in the 50-100 MW range. It should be designed such that test elements can be inserted and removed in an efficient manner, with short turnaround time. It must also be located close to a Post Irradiation Examination (PIE) facility with hot cell disassembly capability. The facility will also require an effluent containment and cleanup system.

The "Nuclear Furnace-like" facility will probably operate throughout the entire ground test and development program. New element designs will always require this type of testing. Design margin testing of fuel elements can also be conducted here to satisfy safety issues. This facility can also provide a hot hydrogen, high radiation environment required for developing non-reactor components, such as sensors and other instruments.

The test objectives for this test will include:

- obtain fuel element performance data for several fuel element types at prototypical operating conditions,
- obtain design margin data for fuel elements by operating up to and including, failure,
- obtain safety performance data, including fission product data as a function of power, temperature and time, and failure mode data
- demonstrate technology readiness for fuel elements

4.2.3.2.6 Reactor/Engine Testing

Full reactor tests must be included in the test program to validate technology readiness (TRL-6).

4.2.3.2.6.1 Low Power Critical Test

Critical assembly tests must be performed as part of the reactor development process. These tests will provide information on power generation distribution within the reactor. This test will also provide information on control element worth, doppler and temperature coefficients, delayed neutron fractions and neutron lifetime, material reactivities, and clustering interactions. There may be a requirement to mockup a "disturbed" core configurations for safety studies. It does not appear that new critical experiment facilities will be required to satisfy the development needs of this program.

The test objective is to obtain benchmark physics understanding and design confirmation on specific concept designs.

4.2.3.2.6.2 Engine Integration

An engine integration test facility is required to study interactions between various components. Physical and operational interfaces, functional capabilities, and interrelated transient effects will be verified.

4.2.3.2.6.3 Cold Flow Tests

Cold flow tests will be required of (either fueled or unfueled) reactor assemblies, to verify and validation turbopump "boot-strap" startup capability in a simulated space startup environment. This should include cryogenic cold soak capability, vacuum, and restart capability. This could be a very important test for several of the concepts proposed, in which the mass is small and the latent heat of the system is very low.

4.2.3.2.6.4 Reactor Tests

After fuel elements have been qualified in a "nuclear furnace-like" facility, and other components have been tested in a high radiation, hot hydrogen environment, full reactor assemblies must be tested. This may require a number of test cells, configured to start with a relatively simple reactor test, using a facility driven pump, and continuing through a full nuclear engine stage test. It is anticipated that no less than three cells will be required, with growth capability for more cells desirable. It is anticipated that the test facilities can be completed in time to test the hardware produced in the technology development program, but very long lead time and cost necessitate an early start.

The first test cell should be planned with a hot hydrogen pump drive capability, independent of the engine, so that startup feedback can be decoupled. It is envisioned that a normal test sequence would begin with criticality tests, followed by partial power runs, full endurance tests, and finally transient operation tests.

An effluent cleanup system will be required to remove radioactive particles and gases from the propellant in these tests. A system of this type was used in the NERVA Nuclear Furnace tests described earlier, (Ref. 41, 77). A radioactive engine-removal capability will be required, so that engines can be transported to the disassembly and PIE facility. The ability to simulate possible malfunctions on the engines may also be required to evaluate reactor control and health monitoring capabilities.

The test objectives for this test series are:

- obtain performance data on complete reactor systems operating at prototypical conditions,
- obtain safety performance data for normal operating conditions, including fission product release rates as a function of operating life, fuel element interaction effects, reactivity coefficients, and thermal hydraulic effects,
- obtain design and off-design performance data to verify technology readiness for reactor health monitoring and control systems,

4.2.3.2.6.5

Engine Ground Tests

These tests will be devoted to validating technology readiness for a full engine stage, including radiation shields, the cooled nozzle (the uncooled portion of the nozzle would not be tested in this test), system turbopumps, feed lines, valves and propellant tanks. The tests performed here will qualify the complete stage as prototypically as possible.

The test objectives for the engine ground test series are:

- obtain performance data on complete engine configurations operating as close as possible to prototypical flight conditions,
- obtain safety performance data for normal operating conditions, including interactions between the reactor and other engine systems,
- obtain design and off-design performance data to verify technology readiness for engine health monitoring and control systems,

4.2.3.2.6.6

Flight Qualification

Ground Testing: Flight hardware certification starts with the "Authority To Proceed" in about 1998, and ends with approval for flight at the "Flight Readiness Review," in about 2007, see figure 37. Certification must address mission and associated stage functions, the launch environment, the mission, and the space environment. Rigorous testing at the component and sub-system level and a comprehensive design review process will be emphasized. The NTP technology panel estimated that two unfueled (no fissile material) reactors would be required for structural and pathfinder/cold flow testing. A minimum of four development reactors will be required, and two flight qualification engines will probably be needed. Add to these the engine that will be flown on the first flight, and a total of at least nine engine systems will be required for initial certification.

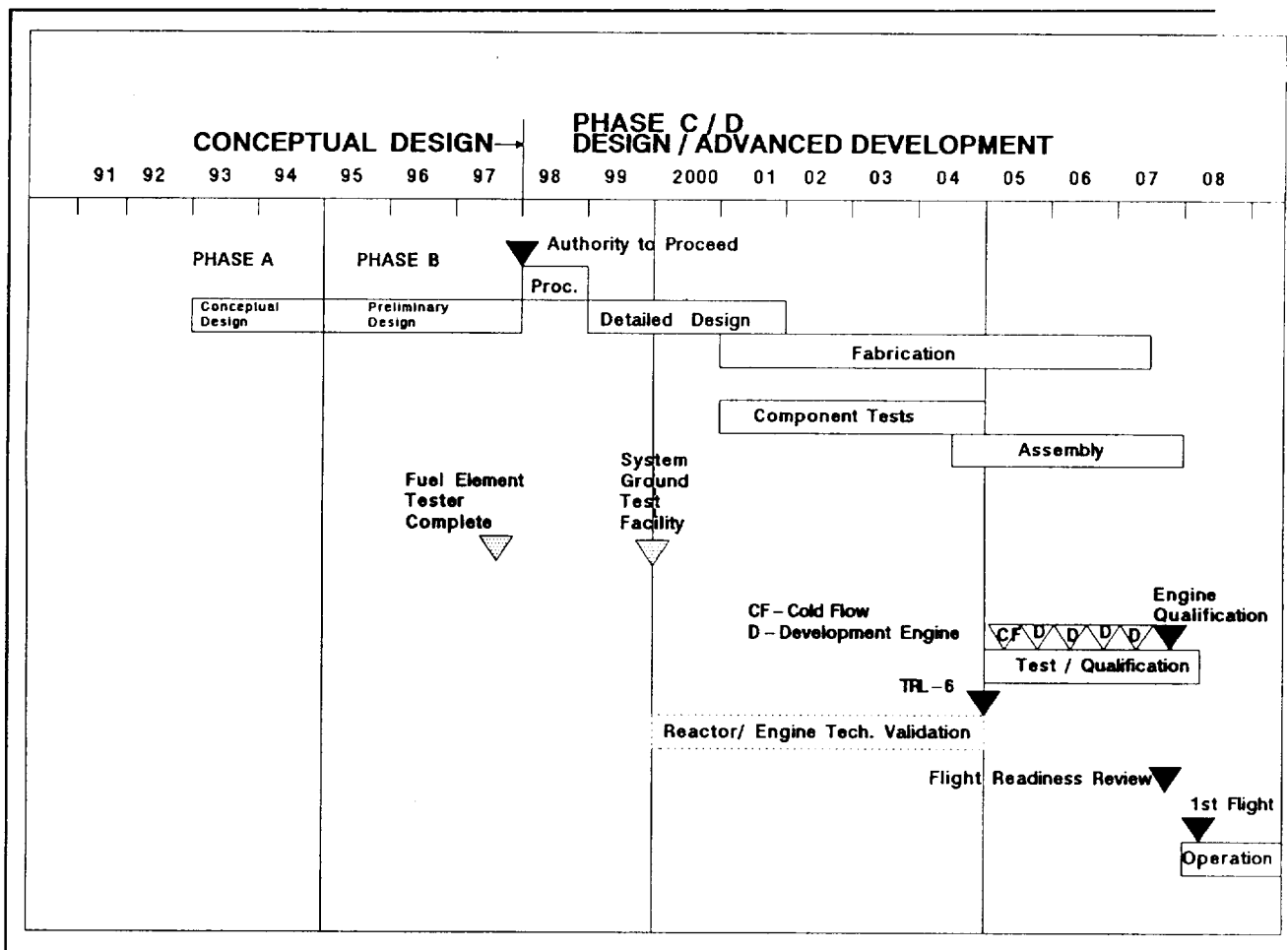


Figure 37 Proposed NTP Engine Development Schedule

Early initiation of the flight system certification program, the "concurrent engineering approach" described earlier, will simplify and minimize the cost of the development program, and will be necessary to meet a "first-flight" target in 2008. If a first flight is desired earlier than 2008, then "Authority to Proceed" must occur about ten years earlier than the desired flight date. An earlier flight decision would naturally put real pressure on the system test facility schedule.

Space testing: It is anticipated that several engine performance parameters can only be tested in the actual space environment. High expansion ratio, full size nozzles can probably only be tested efficiently in space. Space startup, shut down, and decay heat removal cannot be simulated completely on the ground. The actual effects of clustering engines will require the space environment for final proof testing. The in-flight radiation fields cannot be simulated on the ground, and will only occur in space. Long term propellant storage and engine restart must be accomplished in space prior to performing a manned Mars mission. Early space operations, including unmanned robotic, and manned lunar flights, will provide the operational

experience necessary on which to confidently proceed to a manned Mars mission. Similarly, handling, checkout, and launch experience can only be obtained by actual flights. Finally, long term disposal can only be verified by actual in-space activities.

4.2.3.2.7 Component Testing

Early activities in the technology development program will be focussed on engine components. A parallel analytical and experimental program should be used.

4.2.3.2.7.1 Nozzles

Nozzle development is strongly affected by the overall engine design. The nozzle for a nuclear thermal rocket will probably be different from current chemical nozzle designs. An NTR nozzle must account for high energy radiation heating, as well as thermal radiation and convection heating. The nozzle will probably require regenerative cooling, at least in the throat area. It must accomodate a bleed port to drive the turbopump, if a hot bleed cycle system is used. It will probably require a much larger expansion ratio than designs that operate in the atmosphere. Nozzle designs must be developed as part of the conceptual design studies. Once the conceptual designs are available, fundamental material irradiation and hot hydrogen exposure and hydrogen heat transfer tests can begin. The implications of very large nozzle sizes must be studied: structural, vibrational, and in-space assembly.

The proposed nozzle development program, shown on figure 38, includes subscale, segment and truncated nozzle testing; nozzle trade-off studies, conceptual design studies, and detailed hardware design; and nozzle modelling and code development. Initial nozzle trade studies and system conceptual designs will help to focus the hardware test activities. With this approach, the nozzle technologies can be validated with extensive computer modelling and minimum facility requirements (no facility is recommended to test a full-up 500:1 area ratio nozzle). Issues regarding the interface between the uncooled nozzle and the cooled nozzle will be addressed in the segment tests to validate the nozzle design. Validation testing of the full scale nozzle would be accomplished during on-orbit, space-based robotic tests, on the first NTR flight.

4.2.3.2.7.2 Turbopumps

Turbopump technology development is also strongly constrained by the overall engine design. The turbopump for a nuclear thermal rocket may be quite different from current chemical turbopump designs. The fluid mechanics of turbopump design are well understood, and computer codes for hardware design will be reviewed and appropriate computational methods will be selected and/or updated. However, material considerations will probably dominate the development process. The nuclear radiation heating environment will likely make some material choices undesirable. The hot and cold hydrogen environment may also present

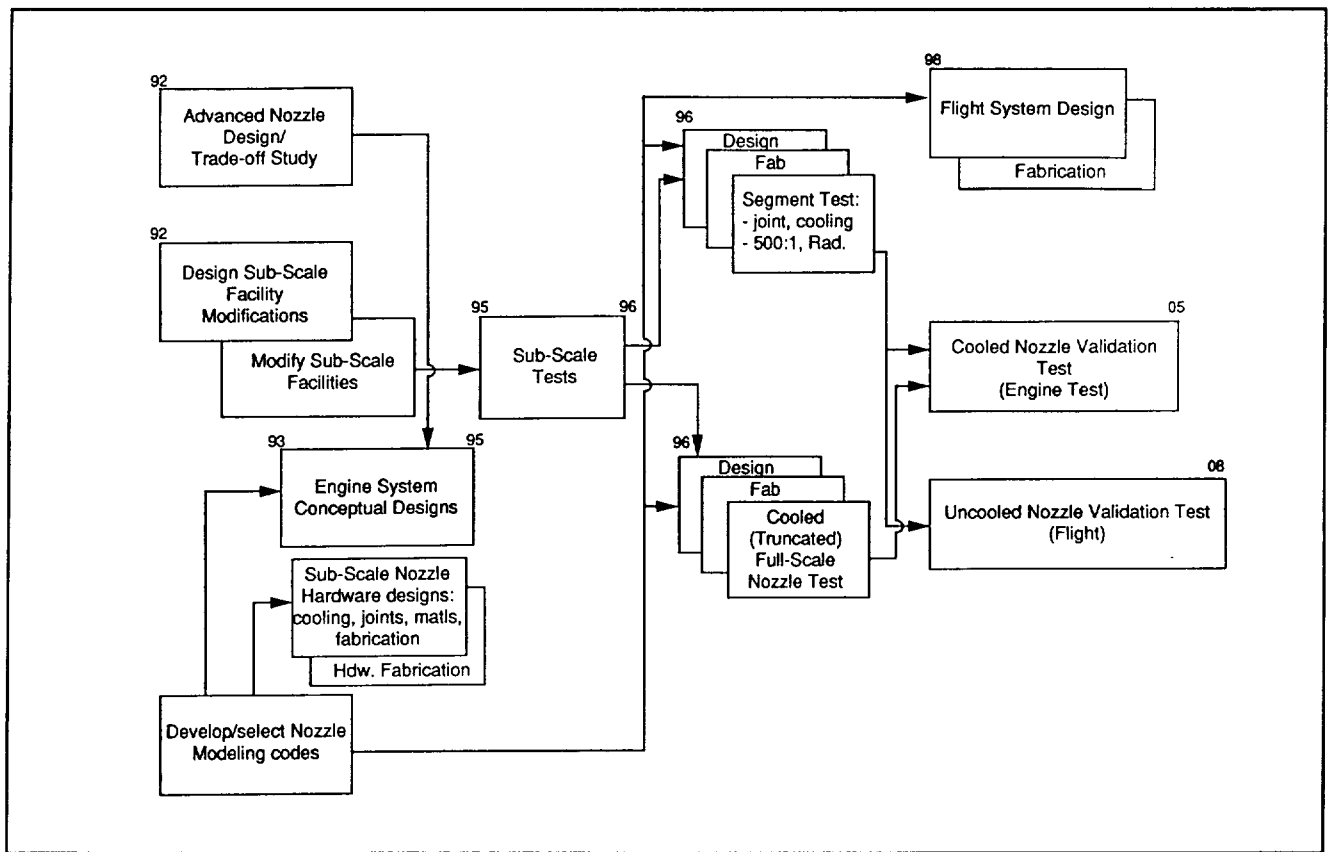


Figure 38 NTP Nozzle Technology Development Program

material challenges. Operating regimes for the turbopump will be dominated by whether a bleed power cycle or a topping (full flow) cycle is chosen, (Fig. 39). Each cycle has some advantages, and the overall engine conceptual design will determine which cycle is ultimately selected. The bleed cycle will require a very high temperature turbine drive and a low volumetric flow rate. The topping cycle will require a relatively low temperature turbine but a large volumetric flow rate. The cycle will also have an impact on the flow paths through the engine.

The low pressure concept may not require a turbopump. However, well-characterized, modulating valves may be required for this system. Once the conceptual designs are available, fundamental material irradiation and hot hydrogen exposures can begin. Since it will be necessary to test turbo-pumps in the combined thermal and radiation environment, it may be possible to coordinate turbopump development testing with the "nuclear furnace-like" testing. The same can be said about the system valves and other components for most of the proposed designs.

4.2.3.2.7.3

Instrumentation/Controls

Instrumentation Development: Certain instrumentation development will be system dependent, and therefore, must wait until the major conceptual design studies are completed. However, it is clear that the

development of instrumentation in several areas, will enhance the success and safety of the development program, and should be started immediately. A new generation of neutron detectors is required to measure neutron flux directly, and in a timely way. A new generation of temperature measuring devices, in the hot hydrogen environment, will be essential for this program. Position, flow and pressure sensors are also required to operate for several hours, for multiple cycles, at high temperatures, and in a high radiation flux environment.

Computer Module Development: Given the automation required to perform the SEI missions, improved, radiation-hardened, electronics and computer technology will be required to monitor and manage the control systems. In many cases, the environments will be too "hot", both from heat fluxes and radiation fluxes for our current systems. Adding shielding and insulation may solve some of these problems, but these tend to be weight-intensive approaches. A computer technology development program conducted in parallel with system development, will be required to accomplish autonomous system operation.

Control Law Development: The science of computer control of space systems and nuclear reactor systems has advanced significantly since the APOLLO/SNAP-10A days. The application of this technology to a remotely controlled nuclear rocket engine will be a development effort that must proceed in parallel with the engine hardware development.

Control System Tests: The control system development process will require a simulation laboratory to develop the engine/stage control system. This laboratory will start out as a pure software facility and progress to part software, part hardware simulation as design components become available. Instrumentation and control hardware will be tested in all of the adverse environments indicated above. It will then be tested as an integrated system on an early reactor or the "nuclear furnace-like" facility. As lightweight components will be desired for the flight systems, they will have to be tested on the actual engines as no other facility has the correct environment. This will require a robust backup control system available at the test cells.

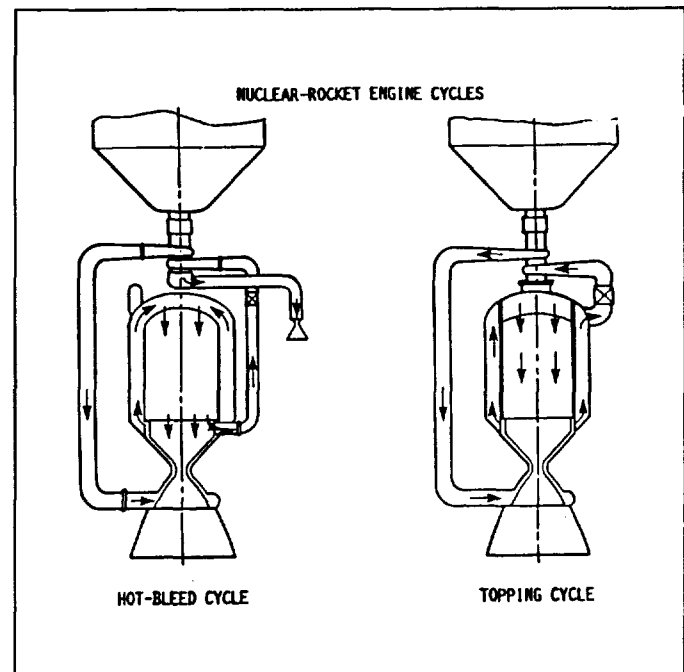


Figure 39 Hot Bleed Cycle and Topping Cycle Engine Schematics

4.2.3.2.8

Safety Tests

Component And Sub-System Safety Tests: All components and sub-systems critical to the safety of the mission will require extensive testing to verify their performance under normal and accident conditions. Testing and/or analysis will cover the launch pad fire environment, impact on land or water, reentry phenomena, and end of life disposal. All realistic malfunctions will be simulated, and system performance verified to remain within safety specifications.

System Safety Tests: System safety tests will be defined as the need arises. System safety tests can not be determined until a design is completed and a mission defined. System safety tests may have to be performed if they are required to resolve a safety issue. It is far better to design in safety, and test components and sub-systems for performance under accident conditions, than to rely on major systems safety tests to resolve critical safety issues. The facilities exist for system safety testing and they will be performed, as required.

4.2.3.2.9

Hot Hydrogen Testing

Hot hydrogen testing capability will be required to test many components and subsystems in a hot hydrogen environment before assembling the first nuclear engines. Fuel element testing in an electric furnace proved very successful during the NERVA program and can have a significant effect on development time in this program. The two major ex-core subassemblies that will require hot hydrogen testing are the turbopump assembly (TPA) and the nozzle. The TPA will require significant hot hydrogen testing to match the turbine and pump performance maps. It will be necessary to demonstrate a throttling capability for the TPA. Startup, shutdown, cooldown, and soakback testing will have to be accomplished on a full TPA prior to engine installation. And of course any advanced materials that are used will have to be thoroughly tested for compatibility. The nozzle assembly will have to be tested for erosion and joint seal leaks. Throttle valves, "hot" sensors, and ducting will all have to be tested in a hot hydrogen environment prior to engine testing.

4.2.3.3

NTP Major Test Facility Requirements

The Solid Core Sub-panel worked very closely with the Facilities Panel to define major NTP facility requirements. These requirements were sent to the Steering Committee in a letter dated May 21, 1991, from the Head of the Nuclear Propulsion Office at Lewis, with the concurrence of the Chairmen of the NTP Technology Panel and the Chairman of the Nuclear Test Facilities Panel. These requirements are summarized in Tables V and VI for an engine test article, and support infrastructure requirements, respectively, for a full system ground test facility and a fuel element test facility. Table VII - X presents top level test objectives developed for these major facilities.

Table V SEI Full Size Engine Test Article Requirements

<u>Requirement</u>	<u>Nominal Value</u>	<u>Range</u>
Thrust:	75,000 lb	30,000-250,000
Configuration:	Single engine Topping or bleed cycle	1-3 engines —
Nozzle:	Two-piece, 10:1 cooled	Altitude simulation for low pressure concept (TBD)
Chamber pressure	1000 psi	500-1500 psi
Mixed Mean Exhaust Temp.	3000° K	2500-3600° K
Coolant Supply:	Liquid hydrogen 25 K 50 psia	— 20-40 K 25-100 psia
Thrust vector control:	+5°	0-5°
Dual mode:	No dual mode	50 kW max. steady state
Maximum single burn:	1 hour	1-2 hours
Total run time/engine:	4.5 hours	1.5-4.5 hours
Restarts:	24	1, 4, 24
Engine control:	Redundant systems	—

These test requirements are planned to be used to initiate facility engineering studies in FY 1992, to further refine these requirements and to develop conceptual designs for these major test facilities. These studies would also assess the impacts on facility cost, schedule and scope of changes in the requirement "nominal value", over the range indicated in Table V.

4.2.3.3.1

Fuel Element Tester

Table VI Additional Support Infrastructure and Capability Needs for NTP Engine Test, Reactor Test, and Fuel Element Test Reactor Facilities

- 1. Assembly and Experiment Preparation Area**
- 2. Reactor Cells(s)/Building**
- 3. Process Fluids Supply**
- 4. Effluent Treatment System**
- 5. Disassembly and Inspection Building**
- 6. Reactor/Site Control Complex**
- 7. Administrative Center**
- 8. Safeguards and Security System**
- 9. Waste Management Facility**
- * Turbopump Power Supply Capability Also Needed for Reactor Test Facility.**

NOTE: Some of the above facility infrastructure and capabilities could be common to some or all of the above major test facilities.

This major new facility (sometimes called a Nuclear Furnace) will be required to test a large number of prototypical fuel elements in a relevant power density and neutron flux, with hydrogen cooling. It must be a standalone facility capable of fast turnaround between tests, and include an effluent cleanup system to remove contaminants from the propellant downstream of the test. Remote disassembly and post-irradiation examination capability must be included. The facility must be capable of testing elements to failure in order to determine design margins. Non-fuel components (electronics, valves, etc.) may also be tested in this facility.

4.2.3.3.2 Reactor/Engine Test Facility

This major test facility complex will include multiple test cells for engine integration, reactor tests (both cold flow and nuclear), and full engine systems (run tank, turbopumps, valves, lines, regeneratively cooled nozzle, and reactor). The complex may also include the prototypic Fuel Element Tester facility. The panel agreed that the facility should be designed to test a single 30,000 to 250,000 lb_f thrust engine (nominally 75,000 lb_f), including the regeneratively cooled nozzle (to an area ratio of about 10:1), with nozzle chamber temperatures from 2500 to 3600 K. Although a cluster of engines may be utilized for the mission, the panel agreed that ground testing of full size engine clusters was not necessary. Past NERVA experience (Ref. 78), and recent calculations indicate small, and predictable thermal and neutronic

coupling between engines. Hydrogen supply will be required for one to two hours continuous firing, and multiple restart capability. A full effluent cleanup system must also be provided. This facility will also be used to perform the flight system qualification testing.

Table VII NTP Major Facility Test Objectives/Requirements

Facility	Test Objectives	Top-Level Facility Requirements
NTP Engine Test Facility	<ol style="list-style-type: none"> 1. Obtain performance data on complete engine configuration(s) operating as close to flight conditions as can be achieved on the ground. 2. Obtain safety performance data as possible limited variations to from normal operating conditions. 3. Obtain information on off-normal operations and operations at the qualification level. 	<ol style="list-style-type: none"> 1. NTP Engine Test Facility will be colocated on same site as Reactor Test Facility with maximum efficient use of same support infrastructure. Multiple test cells are anticipated for redundancy and to prevent scheduling conflicts. 2. Test cell capable of supporting operations meeting capability requirements for engine system verification. Operating Assumptions: Single Engine Tests with a Total Power up to 2000 MW Maximum Allowable Normal Operating Exhaust Pressure at Nozzle Exit: TBD Thrust Vector Control Operation: 0 to 5s Exhaust Chamber Pressure: 500 to 1500 PSIA Mixed Mean Exhaust Temperature: 2500 to 3600°K Coolant Supply: Liquid H₂ 20 - 40°K 25, to 100 PSIA Topping or Bleed Cycle for Turbopump Maximum Single Burn: 1-2 hours Cumulative Reactor Run Times: 1.5 to 4.5hrs Restarts/Cycles: Up to 24 3. Test Cell has capability to test alternate solid core concepts. 4. Test cell has capability to include close coupling of lower portion of propellant tank. 5. Test complex capable of complying with all environmental and safety regulations. 6. Process fluids supplied as required for both operations and post-test decay heat removal according to specification. 7. Effluent Releases within regulatory limits and as-low-as reasonably achievable. Flaring of exhaust hydrogen is baseline. 8. Robust instrumentation capability provided for meeting both operational requirements as well as experiment data acquisition needs. (~1000 Channels of experimental data anticipated) and/or as-applicable ability to efficiently interface with transport system to off-site inspection/examination facilities. 9. Post-test examination and handling capability. 10. Interim storage of test articles accommodated. 11. Facility accommodates efficient, decontamination, decommissioning and waste disposal. 12. Facility complies with applicable security and safeguards requirements.

Table VIII
(Con'd)

NTP Major Facility Test Objectives/Requirements

Facility	Test Objectives	Top-Level Facility Requirements
NTP Reactor Test Facility	<ol style="list-style-type: none"> 1. Obtain performance data on complete reactor configuration(s) operating under prototypical conditions. 2. Obtain safety performance data as possible from normal operating conditions, including fission product release rates, reactivity coefficients, and flow stability. 3. Obtain information on off-normal operations and operations at the qualification level. 	<ol style="list-style-type: none"> 1. NTP Reactor Test Facility will be colocated on same site as Engine Test Facility with maximum efficient use of same support infrastructure. Multiple test cells are anticipated for redundancy and to prevent scheduling conflicts. 2. Test cell capable of supporting operations meeting requirements for reactor system verification. Operating Assumptions: Total Power: Up to 2000 MW Exhaust Chamber Pressure: 500 to 1500 PSIA Mixed Mean Exhaust Temperature: 2500 to 3600°K Coolant Supply: Liquid H₂ 20-40°K 25-100 PSIA delivered to turbopump Maximum Single Burn: 1-2 hours Cumulative Reactor Run Time: 1.5 to 4.5 hrs Restarts/Cycles: Up to 24 3. Test cell has capability to test alternate solid core concepts. 4. Capability available to use either a facility or test article turbopump for high pressure fluid supply. Test complex can supply necessary power required to operate turbopump that is not integral with reactor being tested. Nominal power requirements range from 35 to 350 MW. 5. Reactor complex capable of complying with all environmental and safety regulations. 6. Process fluids supplied as required for both operations and post-test decay heat removal according to specification. 7. Effluent Releases within regulatory limits and as as-low-as reasonably achievable. Flaring of exhaust hydrogen is baseline. 8. Robust instrumentation capability provided for meeting both operational requirements as well as experiment data acquisition needs. (~1000 Channels of experimental data anticipated) 9. Post-test examination and handling capability and/or as applicable ability to efficiently interface with transport system to off-site inspection/examination facilities. 10. Interim storage of test articles accommodated. 11. Facility accommodates efficient decontamination, decommissioning and waste disposal. 12. Facility complies with applicable security and safeguards requirements.

Table IX NTP Test Facility Test Objectives/Requirements (Con'd)

Facility	Test Objectives	Top-Level Facility Requirements
NTP Fuel Element Test Reactor	<ol style="list-style-type: none"> Obtain performance data on one or more types of fuel elements under prototypical NTP operating conditions including: <ul style="list-style-type: none"> Power density Run time Temperatures Coolant type, pressure, temperature, flow rate and contaminant level Cycle behavior Obtain data on design margins by testing fuel elements up to and through failure thresholds. Obtain safety performance data including: <ul style="list-style-type: none"> Fission product release under both normal prototypic and greater severity environments. Failure mode data Perform technology validation of fuel elements. 	<ol style="list-style-type: none"> Test reactor configuration capable of simulating desired prototypical operating and transient conditions to fuel element(s) being tested. Operating Assumptions: Total Power: >30MW Power Density: Prototypic Value for given concept (2 to 20 MW/l) Exhaust temperature: 3000-3500°K Pressure: 500 - 1500 PSIA Duration/Cycles: Sufficient to test elements beyond design basis of engine test article (up to 2 hr single burn, 4.5 hour cumulative burn, up to 24 cycles). Reactor has capability to test alternate fuel concepts with maximum reuse of components feasible. Fast turnaround of element tests possible. Reactor complex capable of complying with all environmental and safety regulations. This includes being able to subject fuel to be tested up to and through failure thresholds as a planned, normal operational event. Process fluids supplied as required for both operations and post-test decay heat removal according to specification. Effluent Releases within regulatory limits and as-low-as reasonably achievable. Robust instrumentation capability provided for meeting both operational requirements as well as experiment data acquisition needs. Capability to test non-fuel components (e.g., electronics, valves, etc.) in NTP environment (i.e., radiation, hot H₂, etc.) Post-test examination and handling capability, and/or as-applicable ability to efficiently interface with transport system to off-site inspection/examination facilities. Facility lifetime and reusability sufficient to last through the entire NTP ground test program. Facility kept as simple as possible to reduce test costs. Interim storage of test articles accommodated. Facility accommodates efficient decontamination, decommissioning, and waste disposal. Facility complies with applicable security and safeguards requirements.

Table X NTP Major Facility Test Objectives/requirements (Con'd)

Facility	Test Objectives	Top-Level Facility Requirements
Remote Inspection/Post Irradiation Examination (PIE) Facilities for NTP Development	<ol style="list-style-type: none"> 1. Conduct Post irradiation inspection, evaluations, and examination of test components and fuel to evaluate performance during tests. 2. Fuel examinations include evaluations of fission gas release, swelling, mass loss, compatibility, etc. 	<ol style="list-style-type: none"> 1. Facility shall be capable of visual and dimensional inspection of all irradiated test components. 2. Facility shall be capable of nondestructive examination, analytical chemistry and mechanical testing of irradiated structural components. 3. Facility shall be capable of evaluating irradiated fuels. This includes burnup analysis, neutron radiography, profilometry, gamma scan, ceramography, fission gas analysis, scanning electron microscopy, (SEM) microprobe, physical property measurements, and analytical chemistry. 4. Facility has efficient interface with system to get articles from test location to examination/inspection location. 5. Facility accommodates efficient decontamination, decommissioning, and waste disposal.

4.2.3.4

"First-Generation" NTP Concepts

The concepts presented at the workshop were reviewed in detail by the Solid Core Sub-panel. Of the solid core concepts presented, it was the consensus that any of the three reactor types (and hence, fuel types), could be developed as a "First Generation" nuclear thermal propulsion system, through full system ground test completion (TRL-6) by 2006, provided adequate funding is provided:

- Prismatic fuel, thermal reactor (NDR, ENABLER II)
- Particle fuel, heterogeneous fuel (PBR, PELLET BED)
- Cermet fuel, fast reactor (prismatic CERMET or WIRE CORE)

In addition, it is believed that several other concepts could also be developed to TRL-6 by 2006, provided (1) they overcome relevant "proof-of-concept" issues, and (2) adequate funding is provided; development of these concepts may be higher cost, (fuel development costs are expected to be relatively low for plasma core systems). These concepts are:

- the low pressure solid core concept,
- the closed cycle gas core "Nuclear Light Bulb" concept,
- the closed cycle vapor core NDR

Proof-of-concept testing and performance analysis of these latter concepts should be a high priority in the project as "Innovative Technology."

Advanced carbide fuel concepts, (such as DUMBO), may also be a candidates, but the technology for carbide fuel must be developed first, and conceptual designs must be completed to demonstrate an advantage over the better known NDR concepts.

It is unlikely that the open cycle gas core concept, the liquid annulus concept, the liquid droplet concept, the FOIL reactor, the tungsten-water moderated concept, the vapor transport fuel pin, or the NIMF concept, could be developed to TRL-6 by 2006.

4.2.3.5

Fuel Strategy

A joint subpanel made up of members of the Fuels/Materials Panel, NEP Panel and NTP panel recommended the following evolutionary fuels strategy; this strategy was summarized earlier in Section 2.2.3 and is shown on figure 3. The strategy includes three difference fuel classes, ranked in priority order. The initial target exit gas temperature for the system will be about 2700 K (with appropriate safety and design margins). As higher temperature fuels are developed and validated, they will be incorporated into reference system designs.

Each of the fuel classes will follow a similar test sequence as indicated on figure 3 and described earlier. Initial efforts will focus on fabrication techniques and property measurements. Hot hydrogen coupon tests will be conducted to measure erosion and corrosion rates in

a non-nuclear test. Next, a nuclear test with hot hydrogen will be conducted to establish a database for fission fragment release, life and corrosion rate as a function of temperature. This data should permit a selection of fuel form or forms to meet fission fragment release requirements.

Next, the fuels will be made into (sub-scale) fuel element configurations, for electric heating tests (coating integrity, cooling performance, etc.). When the prototypic fuel element tester is ready, full fuel elements will be tested in a full nuclear, hot hydrogen environment. Finally, full scale reactor and engine tests are planned to verify technology readiness.

4.2.3.5.1 Prismatic Thermal Reactor Fuels (NDR)

UC-ZrC-C composite fuel is the top priority fuel for the NDR concept for SEI missions. Appropriate coatings will be required for prismatic fuel elements initially to about 2700 K, evolving to binary carbide and/or ternary carbide fuels as they are developed (2900-3100 K).

Advantages:

(1) There is a substantial NERVA database; detailed system design and full system tests have been completed (with duplex fuel); system improvements have been identified.

(2) Composite fuels were tested in nuclear furnace tests in the 1970s to improve corrosion resistance compared to duplex bead fuel.

(3) NDR concept development would be lowest technical risk, lowest cost, and shortest schedule to TRL-6 (Ref. 15).

(4) The concept can evolve to higher performance; higher performance will require binary/ternary carbide fuel development with much more uncertainty.

Disadvantages/Limitations:

(1) The upper limit on composite fuel is probably about 2700 K.

4.2.3.5.2 UC-ZrC Particle Fuels

Particle fuels are applicable to several concepts (PBR, Pellet, Lo-P), and either thermal or heterogeneous reactors (and possibly even fast reactors).

Advantages:

(1) Some manufacturing capability exists, in the high temperature gas-cooled reactor program, and some material properties have been reported (Ref. 79). Conceptual designs have been reported, (Ref. 64,65).

(2) Possible higher fuel temperature capability has been claimed, but must be verified; binary/ternary carbide fuel development is higher risk than composite fuel (Ref. 66). Since there are relatively low structural loads on the fuel particles, the high strength outer sphere is claimed to contain fission products.

(3) Very large surface area to volume ratio maximizes the heat transfer area around each sphere, and the tiny particles have a very short heat transfer path, so the fuel kernel temperature and the sphere surface temperature can be maximized.

(4) Very high bed power density may provide somewhat higher system thrust/weight. A more detailed conceptual design will be required for an astronaut-rated SEI mission to verify this potential. However, there is currently no consensus that high power density or high thrust/weight is required for SEI missions.

Disadvantages/Limitations:

(1) Proof-of-concept testing will be required to verify:

- Mass loss (lifetime) versus temperature at prototypic power generation rates and cooling flow rates
- Flow distribution and control
- Laminar flow stability
- Cold frit/hot frit porosity/flow control

(2) No existing experimental reactor exists that is capable of the very high power densities required to test these fuel elements.

(3) The high surface to volume ratio may also promote higher corrosion rates in the hydrogen flow field, and shorter reactor life at a given temperature.

4.2.3.5.3 Refractory Fuels, Fast Reactor

Some concept design work was done in the 1960s, and fuel processing/fabrication techniques were studied extensively for the nuclear airplane program.

Advantages:

(1) Refractory metal structural integrity may result in improved fission fragment retention by the fuel compared to other concepts; this must be verified early in project.

(2) The rugged construction may offer improved shock loading. Thus, the concept may provide additional safety margins for compaction criticality and immersion criticality.

(3) Cermet fuel development may have application for both NTP and nuclear electric propulsion (NEP) systems. High temperature performance (to 3100 K) has been claimed for cermet fuels.

Disadvantages/Limitations:

(1) System thrust/weight may be lower than other concepts because of higher mass required for fast reactors, thus, performance may be lower. However, if a requirement for very low release of fission fragments is imposed, this concept could be the only way of meeting the requirement. An important effort early in the project will be to evaluate fuel lifetime versus temperature versus fission fragment release for each fuel type in an actual nuclear, hot hydrogen environment.

(2) There may be a temperature penalty for low fission product release, however.

(3) Also, grain growth at high temperature may make for brittleness and loss of fission fragments. The use of a brittle refractory metal for supporting the fuel element could become a critical design issue, and must be carefully considered.

4.2.4 CONSISTENT PERFORMANCE SUB-PANEL RESULTS

The Consistent Performance Sub-panel was established to (1) define a consistent methodology to compare NTP concepts, and (2) initiate the studies required to compare the concepts for the SEI missions, and (3) help define consistent technology development paths for NTP.

4.2.4.1 Methodology

The sub-panel reviewed multiple-criteria decision making processes. Criteria are measures, rules and standards that guide decision making. The criteria include all those attributes, objectives and goals which have been judged relevant in the decision situation. The decision making process then includes selection of the appropriate attributes, objectives and goals.

Attributes are descriptors of objective reality. They are perceived as characteristics of objects or functions that can be identified and measured. Objectives are closely identified with needs or desires; they represent direction of improvement, such as higher performance or lower cost. Goals are fully identified with needs and desires, are assigned specific values a priori, in terms of either attributes or objectives. Figure 40 is a block diagram that describes the process for developing selection criteria for a complex decision. Clearly, requirements drive the entire process, and must be documented, as well as subsequent modifications to requirements. Technical, safety, and functional and operational requirements (F&OR) are defined early in the decision-making process. Next, attributes, evaluation criteria, and weighting factors are selected. Finally, the concepts are reviewed and measured against the selection criteria, and a decision is made and documented.

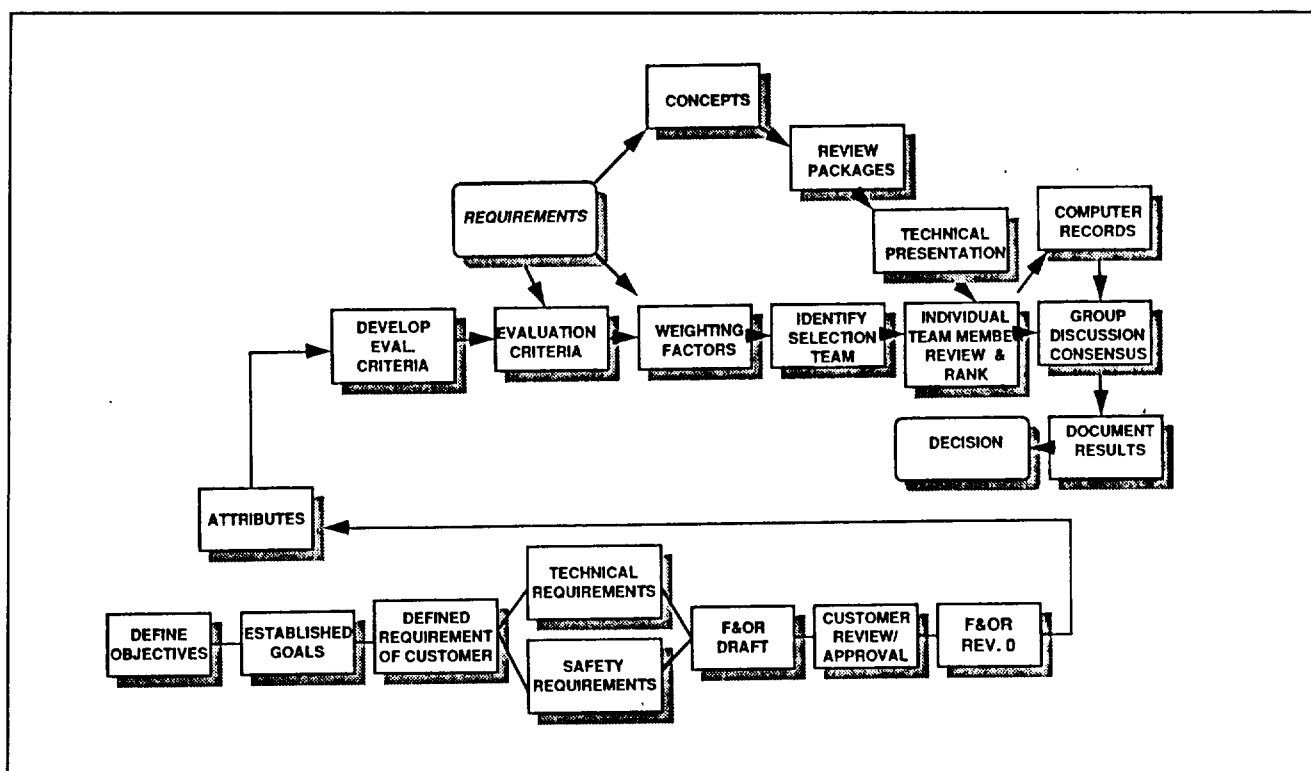


Figure 40 Decision-Making Criteria Development Process

A large number of attributes were identified that could be used to compare various NTP concepts, including:

- engine mass,
- initial mass in low earth orbit (IMLEO), (i.e., number of launches per mission, and hence, launch cost,
- ground testing requirements,
- engine life,
- reliability,
- specific impulse,
- engine run time per mission,
- development risk,
- development time required,
- fuel temperature,
- power density,
- turbine temperature,
- performance growth potential,
- scalability,
- shielding,
- materials, heat flux,
- peak chamber temperature,
- hydrogen composition, dissociation effects,
- vector controls,
- criticality,
- controls, health monitoring,

- nuclear safety,
- overall engine safety,
- toxic materials, and
- operating pressure.

This list is probably not all-inclusive. Also, many of these variables are "primary" variables, such as fuel temperature, pressure, number of engines, and engine run time per mission, and others are variables that are derived from the primary variables, such as thrust, specific impulse, and reliability.

The sub-panel selected the following set of attributes to be used in their preliminary comparisons:

- Specific Impulse, I_{sp} , seconds,
- Initial Mass in Low Earth Orbit, IMLEO,
- Engine Thrust, T ,
- Thrust/Weight, T/W , and
- Nozzle chamber temperature, t_{gas} .

It was recognized by the sub-panel that any comparisons made would be highly dependent on mission requirements, and these requirements must be defined as soon as possible. It should be noted again that when the sub-panel initiated this study, an "all-up," short stay time (opposition-class) manned Mars mission was assumed; more recently the "split-sprint," long stay time (conjunction-class) mission appears to be favored by the mission planners (Ref. 80).

4.2.4.2 Scaling Parameters

A very complex parameter space was identified, that must be included in the selection of NTP concepts for further development. Some of the important variables include:

Concept: Up to 20 different concepts have been identified.

Technology Maturity: NERVA-derivative is the most near-term concept, open cycle gas core concepts are quite far-term, and others are in between.

Engine Cycle: Hot or warm bleed cycle, expander or topping cycle, and tank pressure-fed systems have been identified.

Reactor Fuel Form: A wide range of different fuel forms have been identified, falling in the general classes:

- thermal (NDR, PELLET Bed)
- heterogeneous (PBR, LOW PRESSURE)
- fast (Prismatic CERMET, WIRE CORE)

Fuels are also formed in various geometries, depending on the concept (hexagonal fuel elements, particles, wires, plates, and so forth).

Fuel Temperatures: A wide range of temperatures are claimed for the NTP concepts:

- NERVA duplex beaded graphite, 2200-2500 K,
- NDR composite, 2500-2700 K,
- Binary carbides, 2700-3000 K,
- Ternary carbides, 3000-3600 K,
- Liquid fuels, 3500-9000 K,
- Vapor Fuels, 4000-6000 K,
- Gaseous plasmas, 10,000-20,000 K.

Peak-to-surface temperature: This temperature ratio is a function of the cooling configuration for the concept. With a highly effective heat transfer configuration, the coolant temperature can approach the maximum fuel surface temperature.

Mixed Mean Core Exit Temperature: This temperature is a function of the fuel type and concept as discussed above.

- NERVA graphite, to 2500 K,
- NDR composite, to 2700 K,
- Binary carbides, to 3000 K,
- Ternary carbides, to 3600 K,
- Liquids and gas plasmas, to very high temperatures.

Chamber Pressure: The LOW PRESSURE concept is proposed to operate at about one atmosphere pressure, NERVA was designed for about 450 psia, while current chemical engine state-of-the-art is over 3000 psia.

Nozzle: Expansion ratios up to 500:1 are proposed to maximize specific impulse. Many concepts include a regeneratively cooled nozzle section from 10:1 to 150:1. Uncooled nozzle skirts to 500:1 are proposed with advanced carbon-carbon composites and with more conventional materials (see Fig. 41). Unique nozzle configurations have been proposed, such as plug, and aerospike, that could have a major impact on the engine launch configuration, packaging, and on-orbit assembly.

"Delivered" Specific Impulse: I_{sp} must be calculated consistently, including hot gas kinetics, boundary layer and divergence effects.

Reactor Power Level: A wide range of power levels have been proposed. Mission requirements, including engine redundancy, will drive the engine power levels. NERVA was tested to 1200 MW_t (50,000 lb_f), PHOEBUS to 5000 MW_t (250,000 lb_f). Smaller engines may be required to minimize facility costs and may be desirable to provide redundancy and abort strategies for split-sprint missions (Ref. 81).

Overall Engine Envelop: While this geometry is a function of the concept, the launch vehicle dimensions of about 10 meters diameter by 30 meters long, must be considered in design and concept selection.

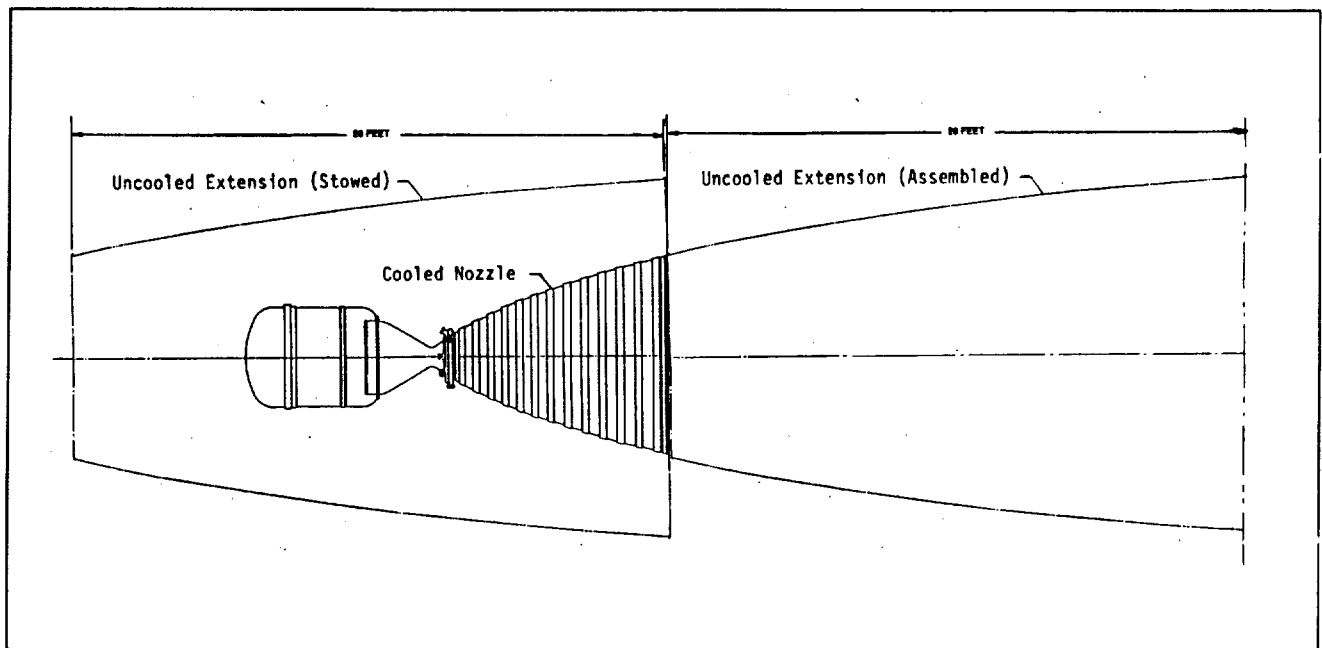


Figure 41 Typical Cooled/Uncooled NTR Bell Nozzle Assembly

Shielding: Some concepts included internal, as well as external shielding, to protect the engine components and electronics. Consistent shielding must be used with each concept to meet the requirements for a manned Mars mission.

Pressure Vessel: Various materials were recommended for the various concepts, such as aluminum, titanium, and carbon-carbon composites.

Engine Controls: Control drums and rods vary with concept. Low pressure concept proposes operating without control mechanisms - using hydrogen reactivity to control neutron fluence. An integrated NTR control system incorporating control drum position, temperature, pressure, and neutron flux sensors (see Fig. 42) must be included in each concept to monitor the system and execute startup, shutdown and health monitoring functions.

Turbopump Assembly: Also concept-specific, several concepts would not include a pump, but would rely on tank pressure to force hydrogen through the reactor system. Man-rating redundancy requirements may strongly influence selection of turbopumps and associated hardware, such as lines, valves and controls. Also, engine cycle selected (topping or bleed) will strongly affect the turbopump assembly.

Run Tank, Main Propellant Tanks: A small run tank, located between the engine and the main propellant tanks, is proposed on several concepts to ensure minimum ullage volume pressurization (Ref. 82). Consistent assumptions regarding tank insulation, shielding and configuration must also be used.

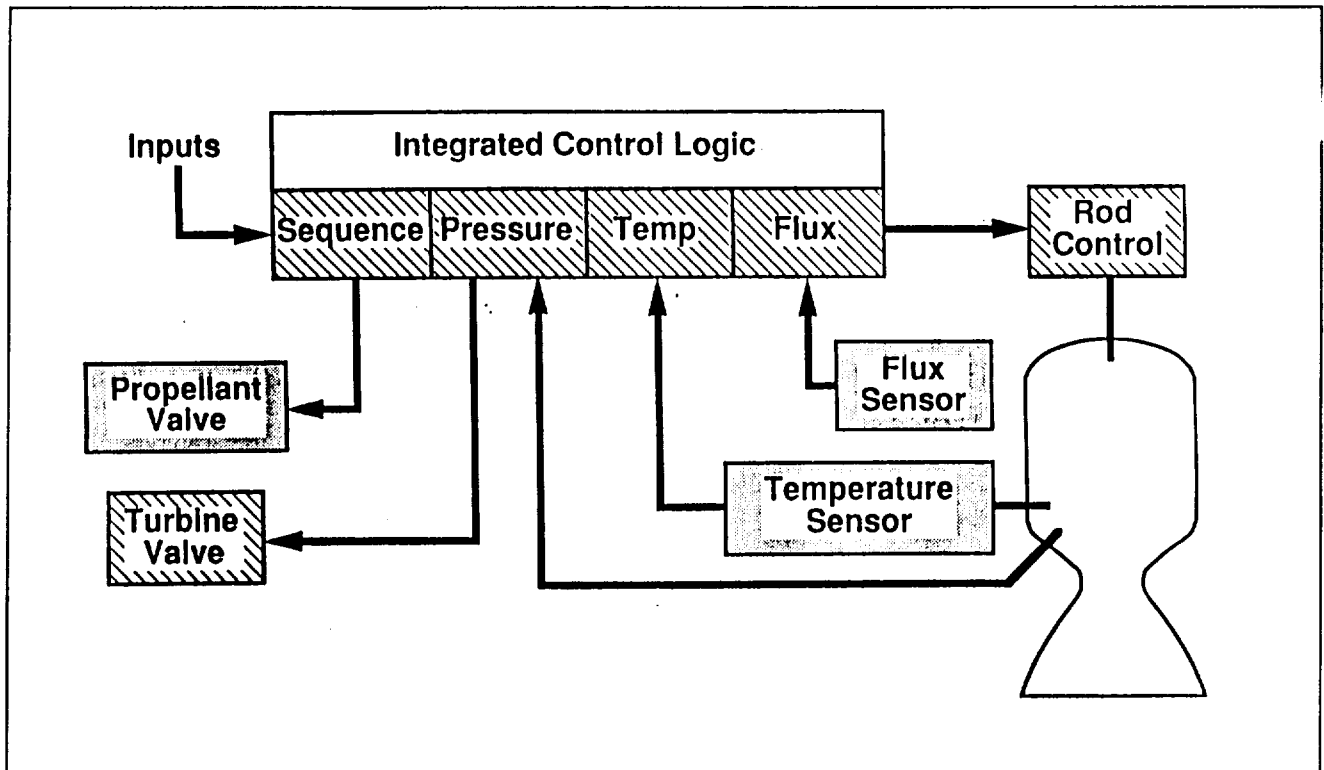


Figure 42 Integrated NTR Engine Control System

Miscellaneous Hardware: Thrust mounting and support structures, gimbal systems, primary and secondary propellant lines, main valves, and secondary valves must all be considered.

Scaling parameters required for consistent scaling of components were identified for general use on all concepts. For example:

- turbopump scaling,
- fuel temperature and lifetime,
- I_{sp} versus temperature versus lifetime,
- electronics characteristics,
- valves and plumbing versus mass versus pressure,
- nozzle weight versus surface area and pressure,
- control systems,
- radiation dose rates, and
- common fault tolerance criteria.

Parametric data have been collected to initiate the studies. Also, the following concepts were selected for the studies (solid core concepts): NDR, PBR, CERMET, Low-Pressure, Wire Core, Dumbo, and Pellet Bed.

4.2.4.3 Results/Status

NDR Concepts: Extensive modelling capability is in place for NDR

concepts, and initial NDR calculations have been made under task order contract from NASA to SAIC and Westinghouse. These results, which were completed after the June NTP panel meeting, are described in detail in reference 83. The methodology described above was used, and the scaling laws developed were based on past ROVER/NERVA engine concept designs, as well as more recent technology developed for the space shuttle main engine and the National Aerospace Plane (NASP). An NTP Expanded Liquid Engine Simulation (ELES) code was updated and used (Ref. 84). Westinghouse supplied the near-term solid-core reactor weight, performance, size and internal shield scaling data. A representative 75,000 lb_f engine design was used to provide the most comprehensive known data point to baseline the code. Then an extensive database was established for a range of operating conditions and thrust.

The following operating parameters were examined:

- Fuel Element/Chamber Temperature

Graphite:	2200-2500 K
Composite:	2500-2900 K
Carbide:	2900-3300 K

- Thrust Levels: 15,000-250,000 lb_f

- Chamber Pressure: 500 and 1000 psia

An expander cycle baseline engine was used including dual, redundant turbopumps, with dual valving for redundancy. Centrifugal turbopumps, typical of the SSME, were assumed. The nozzle design was also typical of the SSME with an uncooled carbon-carbon nozzle extension added.

Specific impulse was calculated to range from about 800 seconds at 2200 K, to about 1050 seconds at 3300 K. Engine thrust/weight varied with thrust level and chamber temperature. For 2700 K and 500 psia:

<u>Thrust, lb_f</u>	<u>Thrust/weight</u>
15,000	1.8
40,000	3.1
75,000	3.8
125,000	4.2
200,000	4.5
250,000	4.8

For 1000 psia and 2500 K graphite fuel, the maximum thrust/weight of 5.5 was reached for a 250,000 lb_f engine. Higher temperature composites (2700 K), and carbides (3100 K) had thrust/weights of about 5.0 and 4.5, respectively, because of the higher density of the fuel.

The baseline NTP engine, with 75,000 lb thrust, expander cycle, composite fuel (2700 K), 1000 psia and nozzle expansion ratio of 500:1 was estimated to weigh 8816 kg (19,440 lb).

Other Reactor Concepts: Scaling data and laws for the PBR and subsequent concepts to be studied were not available for inclusion in the system model in 1991. Thus, a consistent comparison of these concepts is currently not complete. The task remains a high priority, however, and efforts are continuing in 1992, with additional task order contract efforts to develop the models and scaling laws to complete this study. The methodology developed has been very useful in defining these contracts, however. Polansky, a member of the sub-panel, also conducted an assessment of selected concepts (Ref. 31). He describes each of the concepts briefly, and discusses evaluation criteria.

4.2.5 INNOVATIVE CONCEPTS SUB-PANEL RESULTS

This sub-panel was chartered to (1) identify "innovative concepts" - those capable of significant performance improvement, compared to the NERVA technology baseline, (2) define "proof-of-concept" (POC) tests that must be performed before a concept would be developed further, and (3) define a test plan and analytical approach for high-priority innovative concepts. The sub-panel met on February 15 in Gainesville, FL and held a workshop in Boulder, CO on April 2-4, 1991. The subpanel has examined prospective technologies in more detail by meeting regularly during 1991. The efforts and recommendations of the subpanel are discussed in reference 85.

Based of the input received from the NASA astronauts, and the Interagency Mission Analysis Working Group, the technologies that offer very fast transit time to Mars should continue to be developed for a second or third generation NTR transportation system. Approximately ten percent of the budget has been suggested for these activities. Consequently, a Subpanel to investigate advanced concepts was formed from the NTP Technology Panel to examine, compare, and prioritize those nuclear propulsion concepts classified as innovative, that is, those concepts offering very high I_{sp} , but at a very early state of technology readiness.

The Innovative Concepts Subpanel decided to compare advanced concepts other than solid core fuel concepts. Thus, particle bed reactors and the Low Pressure Concepts were not studied. Two exceptions which were included were the Foil Reactor and the direct Fission Product Drive concept. Although these concepts involved solid fuel forms, they were included due to the conceptual nature, non-equilibrium thermodynamics and high I_{sp} offered. In short, the concepts which were evaluated were:

- Liquid Annular Core
- Gas Core: Closed Cycle and Open Cycle

(Note: "Gas" core is used generally to cover droplet, vapor, gas, or plasma fuel form concepts)

- Foil Reactor

- Fission Product Drive
- Explosive driven - push or pull
- Fusion
 - Magnetic
 - ICF
- Antimatter
 - Direct Drive
 - ICF

The goal of the Subpanel was to compare each concept on a "level technological playing field", identify critical issues specific to each concept and identify early proof of concept (POC) experiments which could be performed within the next few years. In essence, a priority list for the concepts would be developed to "guide" the Nuclear Propulsion Program support of research in this area.

The panel determined early that the database supporting the gas core reactor concepts was qualitatively far ahead of many of the other proposed concepts. Therefore, these concepts were evaluated using a procedure similar to procedure used at the NTR workshop. Advocate presentations were made to the subpanel, which then discussed issues, experiments, and technical feasibility. The gas core concepts were evaluated by organizing a Gas Core Workshop in which a much broader scientific constituency was used to evaluate the concepts, identify proof-of-concept experiments, and develop technology plans.

4.2.5.1 Gas Core Workshop

The Los Alamos National Laboratory hosted the Gas Core Workshop in Boulder, Colorado, on April 2-4, 1991. The 33 attendees represented 11 universities, 11 industries, NASA centers, DOE laboratories, and DOE Headquarters. On the first day, advocates presented past research and short synopses of capabilities. On the second day, four working subsessions met in the areas of neutronics, radiation hydrodynamics, materials, and facilities. The output from the subsessions was summarized and submitted to the full NTP panel as recommendations for research.

The performance and mission benefits of advanced concepts were presented. In order to realise Earth-to-Mars transit times of a few months, specific impulses of several thousand seconds are required to deliver the required velocity change to the ship. Solid core NTP systems can not develop these exhaust velocities because of material limitations. However, by utilizing a gaseous or plasma fuel form, where the melting temperature of the cooled containment wall is the constraining factor, Isp's of up to 5000 seconds may be possible.

During the ROVER/NERVA program in the 1960s, significant work was performed on a variety of gas core concepts. In essence, the concepts differed regarding the containment of the uranium fuel and the heating of the hydrogen working fluid. A closed-cycle, physically contained

uranium vortex concept was investigated by the United Technologies Research Corporation (UTRC). Called the Nuclear Light Bulb (see Section 3.3.2), the concept relied on radiative coupling between the uranium fuel and the hydrogen propellant through a fused silica containment vessel. Experimental work on radiation induced opacity, uranium vortex formation, and radiative coupling were performed in the early 1970s. During this time, UTRC demonstrated a radio-frequency heated uranium plasma vortex in a cylindrical silica tube and performed radiation damage studies of the silica. Because of the fused silica interface in the core environment, this concept has a probable I_{sp} range of between 1600 and 2000 seconds. The UTRC continues to be interested in developing this concept.

The coaxial flow open-cycle concept (see Section 3.3.3), which relied on hydrodynamic containment, relied on the hydrodynamic flow pattern of the hydrogen to contain the uranium plasma. Because no solid material was in the core, the potential I_{sp} could reach 5000 seconds. Containing the high temperature plasma fuel, however, is a major obstacle. Although 100 percent containment will not be possible, reducing the fuel leakage rate to acceptably low levels is a major requirement which has yet to be demonstrated. Some experimental data for hydrogen-to-fuel mass flow ratios of a few hundred, has been demonstrated in cold flow simulations in a spherical geometry (Ref. 86). If a mass flow ratio of H_2 to U could be demonstrated at around 400, then the open cycle concept may be justifiable.

4.2.5.2 Results

Although several gas core concepts exist which employ a wide range of temperatures, pressures, and fuel forms, the technological challenges were grouped into four broad categories: neutronics, radiation/fluid dynamics, materials, and facilities. A Subpanel was formed for each of these categories and chartered with the tasks of identifying critical issues in that category for all concepts, critical issues that were concept dependent, and critical proof-of-concept experiments.

The primary technical challenge for each of the groups was the required operating temperature. Because the plasma temperatures will be significantly higher than the wall or moderator temperatures, new thermal protection, heat transfer, and computational capabilities are needed. Neutronically, the cold, moderated neutrons which are reflected back into the core will be upscattered to the chamber temperature. This will tremendously affect power distributions and stability. In turn, the neutron-coupled power distribution will impact the fluid dynamics of the gas, especially the mixing at any interface with injected, cool hydrogen. In addition, the extreme temperatures will demand new materials for walls, nozzles, and containment vessels.

Although these issues and problems are difficult, they are not perceived to be insurmountable. Several nuclear test reactors currently exist to perform basic experimental studies. In addition, numerous high power, high-mass, gas-flow test facilities could be used for the

materials development effort. The facilities Subpanel identified the need for a high power, high temperature clean gas-jet capability. Currently, two 250 kW RF coupled facilities exist, one at the TFA Corporation and the other at Los Alamos. The need for a higher power test stand was clearly identified in order to perform the high fidelity simulation experiments for several concepts. More specifically, the uranium/hydrogen interface, the plasma/materials interface, and the radiation transport in a seeded gas were all problems that could be addressed at such facilities.

Eventually, the gas core concept will have to be demonstrated as a coupled system but, perhaps, at subscale. The nuclear Light Bulb concept is conducive to such a test and could be executed in the relatively near term. The open cycle concepts, however, may require access to the Fuel Element Test Facility (FETF) which is being considered for the Nuclear Propulsion Program. The Subpanel recommended that the FETF be designed to accommodate a large volume cavity containing a uranium gas to demonstrate feasibility once the basic concepts have been proven in the Laboratory.

4.2.5.3 "Proof-of-Concept" Tests

The following sections outline the "proof-of-concept" tests that will be required for gas core concepts.

Neutronics:

- The treatment of neutron scattering in the resonance region must be examined closely.
- Scattering kernels for light molecules (e.g., BeO) must be examined at near-thermal energies.
- Computers to run fully coupled codes may be an issue.
- U^{235} versus U^{233} should be compared as a plasma fuel.
- Experiments to benchmark neutron upscattering must be conducted.

Fluids/Radiation:

- Theoretically investigate temperature and density gradient effects on hydrodynamically contained plasmas.
- Investigate potential for electro-magnetic enhancement of containment in high-density, partially ionized media.
- Perform RF heated experiments to examine plasma/H₂ interface, molecular seeding, and radiation transport.
- Perform cold flow tests to benchmark fluid codes.

Materials:

- Examine nozzle material issues of H_2 embrittlement, transpiration cooling, fission product chemistry, radiation damage, and high melting point.
- Examine storage and handling of UF_6 , UF_4 , and uranium vapor/plasma.
- Perform opacity and erosion experiments on fused silica for varying radiation doses.

Facilities:

- Design laboratory facilities to simulate the radiation environment and/or the thermal environment
- Examine scalability of tests to keep facility costs down.
- Perform in-core radiation damage tests at existing reactors.
- Design large, high-power RF heated test facility for nozzle testing and large scale verification.
- Perform critical assembly tests on subscale fuel "elements".

Overall, the Gas Core Workshop was considered to be successful in that it identified issues and experiments pertinent to developing a gas core propulsion system. In addition, extensive computational and experimental capabilities were delineated for possible research at universities, industries, and government laboratories, which can be utilized to support Gas Core Rocket research. Many workshop participants felt that the gas core concepts could become competitive with the solid core rocket within a few years if adequate funding is provided to successfully complete the proof of concept tests identified.

4.2.5.4 Advanced Concepts

The Innovative Concepts Subpanel also evaluated alternative nuclear propulsion. A summary presentation for each concept was made to the Subpanel by an "advocate." Critical issues pertinent to the concept were then discussed in much the same context as that of the Gas Core Workshop. Ultimately, the concepts were ranked in priority order by the panel. The ranking was intended only as guideline for the innovative concepts technology development, to be included in the Nuclear Propulsion Technology Program. The concepts were:

- 1) Foil Reactor - See Section 3.1.9
- 2) Fission Product Drive
- 3) Liquid Annular Core - See Section 3.2.1
- 4) Explosive Driven Concepts: ORION and Medusa
- 5) Fusion
- 6) Antimatter

4.2.5.5 Conclusions and Discussion

After participating in the Gas Core Workshop and reviewing the other advanced concepts, the Subpanel attempted to reach some general conclusions and make recommendations regarding the various concepts. In general, the panel agreed that some level of support (probably about 10 percent of the total budget for nuclear propulsion) should be focused on the advanced concepts. These concepts offer the potential of breakthroughs in propulsion systems which could dramatically accelerate the exploration of space. By supporting proof of concept experiments in the laboratory setting, feasibility of these concepts may be determined.

The Panel also attempted to prioritize the concepts based on the presentations made to the panel, the presentations made at the NASA/DOE NTP and NEP workshops (summer 1990), and the technical experience bases of the members. An effort was made to incorporate such factors as performance potential, technological risk, testability, safety, crew impact, and current technological status. The following priority list is intended to be a guideline only for the funding of advanced concepts in the nuclear propulsion program. The Panel assessment, however, showed a clear emphasis for the first four concepts and markedly reduced support for the last three ideas.

4.2.5.6 GUIDELINE PRIORITY LIST

1. Gas Core Fission Systems - Open and Closed Cycle
2. Fusion - Emphasis on ICF
3. Antiproton - Direct Heating and ICF
4. Explosive-Driven Concepts
5. Foil Reactor
6. Liquid Annular Reactor
7. Fission Product Drive

In addition, the panel recognized that the Advanced Propulsion part of the program could be a major vehicle for the involvement of universities. Clearly, research laboratories and industry will pursue both the mainline program and advanced concepts, but university research efforts and experimental capabilities may be more compatible to supporting the future concepts.

In order to pursue some of the critical issues identified by the panel, a list of potential critical experiments was compiled. The experiments and the facilities to support the research varied widely from small laboratory scale tests to use of the Nuclear Fuel Element Test Facility planned for the solid core test program. Some of the experiments and studies that were considered necessary in the near term were:

- 1) experimentally examine window opacity versus radiation dose and window/fuel erosion for the nuclear light bulb concept,

- 2) perform open cycle hydrodynamic modeling and further develop fully coupled design codes,
- 3) perform cold flow tests to benchmark fluid dynamic codes,
- 4) perform radio-frequency heated gas jet studies of plasma/gas interfaces, radiation transport, gas seeding, and erosion,
- 5) investigate behavior and material compatibility of UF_6 , UF_4 , and uranium vapor/plasma in simulated operation conditions,
- 6) verify the idea of a magnetic cusp/nozzle using laboratory generated plasmoids,
- 7) perform fully coupled ICF calculations for antiproton driven implosions,
- 8) pursue antiproton storage concepts and perform low energy annihilation cross section measurements, and
- 9) development of transpiration-cooled, high-temperature materials.

Other potential experiments and studies are currently being solicited.

In summary, a subpanel of the Nuclear Thermal Propulsion Technology Panel reviewed several advanced nuclear propulsion concepts. The concepts considered have the potential of producing thrust with a specific impulse of greater than 2000 seconds. Because of the past work on gas core fission systems, these concepts were given the highest priority regarding future support. More advanced concepts utilizing fusion reactions and antiproton reactions were considered to have high potential for very long-range systems. The subpanel concluded with the recommendation that support of Advanced Concepts was necessary for a comprehensive, integrated advanced technology nuclear propulsion program.

5.0 SUMMARY OF RESULTS/DISCUSSION

5.1 TECHNOLOGY READINESS LEVELS OF CONCEPTS

The target date for technology readiness level of 6 (TRL-6 - system ground testing complete) used by the NTP Technology Panel was 2006 for this evaluation. This date has been used to categorize the various concepts into groups that can meet this date, and those that will probably take longer. This date is roughly consistent with the recommendations of the Stafford Synthesis Group Report.

NTP concepts that could be developed to TRL-6 by 2006, if adequate R&D and facility funding is provided:

A. Solid Core Concepts

1. NERVA-derived thermal reactor NDR concept, ENABLER II
 - Graphite matrix fuel (to 2500 K) - (For a possible early development option. The composite fuel is the fuel recommended by the panel).
 - Composite Fuel (to 2700 K)
 - Carbide Fuels (2700-3100 K)
2. Particle Bed Reactor, PBR
 - Carbide Fuel Particles (2700-3500 K)
3. WIRE CORE or Prismatic CERMET (may have fission fragment release advantages) (2500-3100 K)

B. Several concepts are considered to be possible candidates for development to TRL-6 by 2006 (maybe at higher cost) depending upon:

- Improved performance verified via conceptual design studies
 - "Proof-of-concept" test data verification
1. LOW PRESSURE reactor concept with PBR fuel elements or platelet fuels
 2. Nuclear Light Bulb (closed cycle gas core)
 3. Vapor core reactor (closed cycle gas core)

C. The following concepts probably will not be candidates for development to TRL-6 by 2006 because of the higher technical risk:

1. Open cycle gas core
2. Liquid annulus reactor
3. Liquid droplet reactor concept
4. Foil reactor
5. Tungsten-Water-moderated concept
6. Vapor Transport Fuel Pin concept
7. NIMF
8. Advanced DUMBO reactor
9. Pellet Bed Reactor

5.2 CONCEPT SELECTION CRITERIA

The Steering Committee recommended that the panels study the criteria for categorizing the various concepts. After much discussion, the technical panels and working group chairmen agreed that the criteria selected and used at the NTP and NEP workshops in June/July, 1990 remain the appropriate evaluation criteria (Ref. 15):

- Safety
- Development cost
- Performance
- Technical risk

5.3 KEY 1992 MILESTONES

The steering committee recommended that the NTP Panel define key milestones that should be accomplished in 1992. The following milestones were selected to show significant progress on the critical programmatic and technical issues.

1. An approved interagency Memorandum Of Agreement should be approved in 1992.
2. A project Requirements Document, with change tracability should be implemented in 1992.
3. NTP stage and engine requirements should be defined to guide technology developments and concept comparisons.
4. NTP conceptual design contracts should be awarded. (These contracts will not be awarded in 1992 because of budget limits).
5. Detailed test plans should be defined in the fall, 1992:
 - Fuels/materials, nuclear technology,
 - Non-nuclear NTP technology, and
 - Innovative "proof-of-concept" tests.
6. Appropriate nonnuclear hot H₂ test facilities should be evaluated for possible use in the project.
7. Existing nuclear test facilities should be evaluated for possible use in the project.
8. New "nuclear furnace" and NTP system ground test facility conceptual design studies, environmental assessments, and site selection studies should be initiated by DOE as soon as possible.

5.3 SAFETY ISSUES

The steering committee also recommended that the NTP panel should review special safety issues (plus or minus) associated with specific concepts or groups of concepts, to try to identify any inherently safer characteristics that would favor one concept over another from a ground test or flight operations stand point. Safety issues (strengths/weaknesses) were identified at the workshop (Ref. 15) and were presented to the Steering Committee in September, 1990. The NTP panel believes it would be premature to try to make a concept selection based on these preliminary findings. Significant design and analysis

will be required before a meaningful comparison of safety advantages can be made. Virtually all of the claimed advantages for the advanced fuels and concepts must be verified by experiments.

5.4 EVOLUTIONARY FUELS STRATEGY

The recommended evolutionary fuel/coatings development strategy has been discussed above in Section 2.2.3, Section 4.2.3.2, and 4.2.3.5, and will not be repeated in detail here. In summary, the strategy would develop NDR fuels, advanced carbide fuel particles, and Cermet fuels. The initial target fuel would provide a reactor mixed mean outlet temperature of about 2700 K. The fuels technology is expected to evolve to higher temperatures, as more advanced fuels are discovered and experimentally verified. Fission fragment release policy is expected to be a major factor in concept selection.

5.5 NEAR-TERM NTR ENGINE

It was recognized at the NTP workshop and reiterated by the panel, that a nearer-term NTR engine option exists, that would utilize somewhat up-graded NERVA technology, to have a nuclear engine for lunar operations by about 2002-2005. Griffin (Ref. 87) has strongly endorsed an early return to the moon, with initial flights before the end of this century. A NERVA-derived system probably could be developed in that time period, if an "Authority-to-Proceed" were granted quickly, and adequate development funding were provided. The ground test facility may still be the pacing item in the development schedule, however. A separate "Fuel Element Tester" would probably not be required, however, since the power densities in existing experimental reactors would be adequate to test NDR fuel element clusters. The total cost of developing a near-term NTR engine would probably be much less than the test and development program described in this report.

The "Concurrent Engineering" approach described and recommended earlier, would be critical to the earlier implementation of nuclear thermal rocket systems. With this approach, flight system design, engineering and hardware development would be an integral part of the technology development project, and the hardware tested and validated in the ground test facilities would be "flight" hardware or very close to flight hardware. With this approach it is expected that significant savings can be made in overall development time and cost. The system performance would probably be less: on the order of 800-850 seconds specific impulse, instead of 925 seconds. This near-term option will be studied further in the months ahead.

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13. ABSTRACT (Maximum 200 words) The NASA Lewis Research Center was selected to lead nuclear propulsion technology development for NASA. Also participating in the project are NASA Marshall Spaceflight Center and the Jet Propulsion Laboratory. The U.S. Department of Energy will develop nuclear technology and will conduct nuclear component, subsystem, and system testing at appropriate DOE test facilities. NASA program management is the responsibility of NASA/RP. The project includes both nuclear electric propulsion (NEP) and nuclear thermal propulsion (NTP) technology development. This report summarizes the efforts of an interagency panel that evaluated NTP technology in 1991. Other panels were also at work in 1991 on other aspects of nuclear propulsion, and the six panels worked closely together. The charters for the other panels and some of their results are also discussed. Important collaborative efforts with other panels are highlighted. The interagency (NASA/DOE/DOD) NTP Technology Panel worked in 1991 to evaluate nuclear thermal propulsion concepts on a consistent basis, and to continue technology development project planning for a joint project in nuclear propulsion for the Space Exploration Initiative (SEI). Five meetings of the panel were held in 1991 to continue the planning for technology development of nuclear thermal propulsion systems. The state-of-the-art of the NTP technologies was reviewed in some detail. The major technologies identified were: fuels, coatings, and other reactor technologies; materials; instrumentation, controls, health monitoring and management, and associated technologies; nozzles; and feed system technology, including turbopump assemblies.				
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